Evaluation of Arm-Leg Coordination in Flat Breaststroke

Abstract

This study proposes a new method to evaluate arm-leg coordination in flat breaststroke. Five arm and leg stroke phases were defined with a velocity-video system. Five time gaps quantified the time between arm and leg actions during three paces of a race (200 m, 100 m and 50 m) in 16 top level swimmers. Based on these time gaps, effective glide, effective propulsion, effective leg insweep and effective recovery were used to identify the different stroke phases of the body.

A faster pace corresponded to increased stroke rate, decreased stroke length, increased propulsive phases, shorter glide phases, and a shorter T1 time gap, which measured the effective body glide. The top level swimmers showed short time gaps (T2, T3, T4, measuring the timing of arm-leg recoveries), which reflected the continuity in arm and leg actions. The measurement of these time gaps thus provides a pertinent evaluation of swimmers’ skill in adapting their arm-leg coordination to biomechanical constraints.

Key words

Biomechanics · swimming · motor control · exercise · performance

Introduction

When switching from the 200 m to the 100 m pace in the breaststroke, the velocity increase combines with an increased stroke rate, a shorter stroke length [5,6,24] and changes in the stroke phases [1,6,23]. More than any other stroke, the breaststroke undergoes wide variations in velocity because of the greater drag components of the forward movement [14] during underwater recovery of both arms and legs [13]. When velocity increases, swimmers increase their stroke rate or reduce their stroke length by shortening the glide time [6,23,24] and change their arm-leg coordination.

Different breaststroke styles have been identified: vertical, flat, undulated, and undulated with overwater recovery of the arms [15,19,25,28,29]. These swimming techniques are all associated with a more or less horizontal position of the trunk [2,19,22,23] but with different levels of energy expenditure [28,29]. At slow velocities, the highest intra-cyclic velocity fluctuations were observed in the undulated style with overwater recovery of the arms [25,28]. Regarding the regression line (VO₂ – velocity) for the flat style, this style “may be somewhat more economical than the undulated style” [29].

The breaststroke thus comprises several techniques and types of arm-leg coordination that change with velocity [6,24]. Nemesi and Vaday [17] tried to quantify the cyclical activity of the arms and legs and their stroke phases. Using a speedometer synchronised with a video camera, Bober and Czabanski [1] associated the stroke phases with swimming velocity. With similar but more advanced material, Craig et al. [9], D’Acquisto et al. [11], and Tourny et al. [25] recorded the fluctuating velocity of

Affiliation

C.E.T.A.P.S. Laboratory UPRES JE 2318: University of Rouen, Faculty of Sports Sciences, Rouen, France

Correspondence

M. Didier Chollet and L. Seifert · University of Rouen, Faculty of Sports Sciences, CETAPS Laboratory · Bld Siegfried · 76821 Mont Saint Aignan Cedex · France · Phone: + 33232107793 · Fax: + 33232107793 · E-mail: didier.chollet@univ-rouen.fr or l.seifert@libertysurf.fr

Accepted after revision: October 4, 2003

Bibliography

the swimmers’ movements. Arm pulls and leg kicks resulted in acceleration, whereas the glide and the arm and leg recoveries resulted in deceleration [11,25]. Wilkie and Juba [30] showed the same stroke acceleration-deceleration using a video camera. In the flat breaststroke, arm and leg recoveries tend to overlap, as the propulsive phase of one pair of limbs occurs during the glide of the other pair [8,15]. The coordination of the undulated style is close to that of the flat style, except in the ascendunt undulation that takes place during a part of the propulsive arm phase [8,15,28,29].

Chollet et al. [4] created a new Index of Coordination (IdC) to quantify arm coordination in the front crawl. Chollet and Boulesteix [3] then calculated four time gaps that characterise arm-leg coordination in the butterfly. Although Persyn et al. [19–21] proposed a computerised evaluation procedure to understand the relationship between arms and legs in the breaststroke, arm-leg coordination in the flat breaststroke has never been quantified.

This study had two aims regarding the flat breaststroke: 1) to measure the time gaps between the arm and leg stroke phases with a speedometer-video system giving the instantaneous velocity of the body, and 2) to study the “effective duration of the phases” related to the time gaps when pace increased. For all swim paces, the time gaps quantified the lag time between actions, the continuity of actions, or a superposition of stroke phases.

**Material and Methods**

**Subjects**

Sixteen French swimmers (9 men: mean age, 19.9 ± 2.3 years; mean height, 185.7 ± 9.9 cm; mean mass, 80.7 ± 8.1 kg; 7 women: mean age, 15.7 ± 1.2 years; mean height, 171.9 ± 2.3 cm; mean mass, 59.9 ± 3.2 kg) participated in this study between 1997 and 2002. This group included a national finalist and international level swimmers whose expertise was expressed in percentage of the world record (% of WR) for the 100 m breaststroke; the mean was 91.4 ± 2.4% for the men and 90.1 ± 2.7% for the women.

**Swim trials**

In a 25 m pool, the swimmers performed three breaststroke trials at successively increasing velocities. Each trial required an individually imposed swim pace corresponding to a specific race distance: 200 m (V200), 100 m (V100), and 50 m (V50). 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 over the 25 m. 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 subject repeated the trial. During the test, pace and stroke rate (SR) were monitored with a chronometer and a Seiko Base 3-frequency meter. These measures served only to validate each trial, i.e., to ensure minimal discrepancy between the swim pace expected of each swimmer and the velocity at which he or she actually swam. The experimental data of this study were obtained by the video device.

**Video analysis**

Two underwater video cameras (Panasonic NV-MS1 HQ S-VHS, Ozako, Japan or Sony compact FCB-EX10L, Ozako, Japan) with rapid shutter speed (1/1000 s) were used at the rate of 50 images per second. One camera filmed the swimmer from a frontal view, the other from a side view. They were connected to a double-entry audio-visual mixer, a video timer, a video recorder and a monitoring screen to mix the frontal and lateral views on the same screen, from which mean SR was calculated. A third camera, mixed with the side view for time synchronisation, filmed all the trials of each swimmer with a profile view from above the pool. This camera measured the time over a distance of 12.5 m (between the 10 m and the 22.5 m marks to suppress the wall constraint) to obtain the velocity. SL was calculated from the mean velocity and SR values.

**Velocity – video system**

Video analysis was synchronised with a swim-speedometer (Fahneimann 12045, Bockenem, Germany) [7,9,11,25]. The swimmers wore waist belts attached by cable to an electric generator. The voltage produced by the generator was proportional to the swim velocity, and this was recorded on computer. The lateral view of the video and the video timer were associated with the instantaneous velocity curve read on the computer (Fig. 1).
Three complete strokes were filmed for each subject. The accelerations and decelerations measured by the swim speedometer (at 1/100 s) were synchronised with the arm and leg movements measured by the video device (at 2/100 s). In fact, this video-velocity system enabled us to determine the key points of both arms and legs and thus to accurately delimit the propulsive and non-propulsive phases.

Arm and leg stroke phases
The arm stroke was divided into five phases (Fig. 2):
1. Arm glide. This glide and catch phase was the time between the extension of the arms and the beginning of the backward hand movement.
2. Arm propulsion. This was the time between the beginning and end of the backward hand movement. This second phase was the initial part of upper limb propulsion.
3. Elbow push. This was the time between the end of the backward hand movement and both the beginning of the forward hand movement and the end of the inward-backward elbow push. This third phase was the second part of upper limb propulsion. According to Maglischo [15], the elbows must be squeezed down and inward only, to overcome the backward inertia of the hand at the end of the arm insweep. This movement of the arms then pushes the hands forward and up into recovery [15]. To obtain a propulsive elbow push, the swimmers must squeeze their elbows and not drop them back against their ribs [15]. Our video-velocity system confirmed that this elbow push was propulsive.
   The propulsion of the upper limbs was the sum of arm propulsion and elbow push.
4. First part of the recovery. This phase was the time between the end of the elbow push and the arm recovery until an arm/forearm angle of 90° was reached.
5. Second part of the recovery. This was the time between the end of the first part of the recovery and the extension of the arms. The arm recovery was the sum of the two parts of the recovery.

Each phase was expressed in percentage of a complete arm stroke duration.

The leg stroke was also composed of five phases (Fig. 2):
1. Leg propulsion. This was the time between the beginning of the backward movement of the feet (the legs being initially in maximal flexion) and the leg extension.
2. Leg insweep. This was time between the leg extension and the joining of the legs.
3. Leg glide. This was the time between leg joining and the beginning of both forward movement of the feet and knee flexion.
4. First part of the recovery. This phase was the time between the end of the glide and leg recovery, until a thigh/leg angle of 90° was reached.
5. Second part of the recovery. This was the time between the end of the first part of the recovery and complete knee flexion, until the end of the forward movement of the feet.

The leg recovery was comprised of two phases [11]: it was the sum of the two parts of the recovery.

Fig. 2  Arm and leg stroke phases in flat breaststroke.
Each phase was expressed in percentage of a complete leg stroke duration.

Based on the instantaneous velocity data, four types of stroke phase were identified: 1) *propulsive phases* (+) during which body acceleration occurred, 2) *negative phases* (−) corresponding to body deceleration, and 3) and 4) *neutral phases* corresponding to either glide (0) or active drag (0°), i.e., to body deceleration. The *propulsive phases* (+) corresponded to arm and leg propulsive phases and the elbow push. The *negative phases* (−) were the underwater recoveries of arms and legs. Arm and leg glides were characterised as *neutral phases* (0) because of the streamlined position adopted by the body.

Conversely, the leg insweep corresponded to an *active drag phase* (0°). A body glide (neutral phase) occurs when the legs are not in a streamlined position because they are not joined. In fact, at the beginning of the insweep, the legs are opposed to an active drag [14] because they are apart and extended before continuing to move inward until they are almost together, i.e., in a streamlined position. The instantaneous velocity data did not confirm the propulsive feature of the leg insweep that Ungerecht [26] explained by a vortex effect. Maglischo [15] and Costill et al. [8] showed that only the first part of the leg insweep was really propulsive; in fact, they called this part the “downsweep” and not the “insweep”.

A complete stroke is divided into four parts, as shown by Craig et al. [9]: 1) leg propulsion (acceleration); 2) leg insweep followed by the glide of the entire body (deceleration); 3) upper limb propulsion (acceleration); and 4) arm and leg recovery (deceleration).

**Arm-leg coordination**

Arm-leg coordination was determined by measurement of the time gaps between the different stroke phases of each pair of motor limbs and this in turn enabled us to analyse the body acceleration-deceleration ([13] in butterfly). Five time gaps were identified (Fig. 3): T1a: between the end of leg propulsion and the beginning of arm propulsion; T1b: between the end of leg insweep and the beginning of arm propulsion; T2: between the beginning of arm recovery and the beginning of leg recovery; T3: between the end of arm recovery and the end of leg recovery; and T4: between 90° arm flexion in arm recovery and 90° leg flexion in leg recovery. This last is a unique feature of the flat breaststroke [6,19,20].

In each trial, each time gap was expressed as percentage of a complete leg stroke (itself calculated as the mean of three leg strokes that were representative of the imposed swim pace).

**Theoretical arm-leg coordination**

When T1a = 0, there was mechanical continuity between leg and arm propulsion. Nevertheless, the beginning of arm propulsion also occurred when the legs were apart and still in active drag. Thus, leg insweep did not occur.

When T1a > 0, the time gap was positive because the arm and leg propulsive actions overlapped to maintain velocity. In fact, this coordination requires great energy expenditure because the upper and lower limbs are not streamlined [14], and only some top level swimmers can perform it in sprint.

When T1a < 0, the time gap was negative and the arm glide and either the leg insweep or the leg glide added to the leg insweep occurred simultaneously.

When T1b = 0, there was motor continuity (because the arm action began when the leg action finished), even if it was not associated with mechanical continuity.

When T1b > 0, it was the same situation as either T1a > 0 or T1a < 0.

When T1b < 0, there was a negative time gap during which the arm and leg glides occurred simultaneously.
When T2 and T3 = 0, there was mechanical continuity between leg and arm propulsion.

When T2 and T3 < 0, there was a negative time gap because a propulsive action overlapped a negative action. In fact, the underwater recovery of one pair of limbs slowed down the propulsion of the other pair, providing neither a mechanical nor a motor solution. Nevertheless, top level swimmers can use this coordination to maintain high velocity, i.e., they do not wait for the recovery of one pair of limbs to end before accelerating by beginning the propulsion of the other pair.

When T2 and T3 > 0, the positive gap corresponded to the glide of one pair of limbs during the recovery of the other pair, so no energy waste was added to the recovery phase because the rest of the body was in a streamlined position.

When T4 = 0, the 90° angle of arm and leg flexion during their respective recoveries was simultaneous; this was a unique feature of the flat breaststroke [6,19,20].

When T4 > 0 or < 0, there was a negative gap indicating the lack of coordination between arm and leg recoveries.

**Effective stroke phases**

Based on time gaps and the relationships between the arm and leg stroke phases, four “effective” stroke phases were found to define the flat breaststroke: 1) effective propulsion, 2) effective recovery, 3) effective glide, and 4) effective leg insweep. The stroke phase duration was called “effective” because, during this time, the two pairs of motor limbs performed only one of the following actions: a propulsive action, a negative action (recovery phase), a neutral action (glide phase), or an active drag action (leg insweep phase).

The **effective propulsion** (Prop<sub>eff</sub>) was the time during which only propulsive action occurred. It was the sum of leg propulsion, arm propulsion and elbow push, except if T1<sub>L</sub> > 0 and if T2 and/or T3 < 0. If T1<sub>L</sub> > 0, arm propulsion overlapped leg propulsion, thus T1<sub>L</sub> was subtracted from the effective propulsion. If T2 and/or T3 < 0, a propulsive phase of one pair of motor limbs overlapped the recovery phase of the other pair, and the duration of T2 and/or T3 was subtracted from the effective propulsion.

The **effective recovery** (Rec<sub>eff</sub>) was not the sum of arm and leg recoveries, but the time between the beginning of the first recovery and the end of the last recovery, except if T2 and/or T3 < 0. If T2 and/or T3 < 0, the propulsive phase of one pair of motor limbs overlapped the recovery phase of the other pair, and the duration of T2 and/or T3 was subtracted from the effective recovery.

The **effective glide** (Gli<sub>eff</sub>) was a phase during which the entire body (including arms and legs) was gliding. It was the time between leg joining and the beginning of arm propulsion, except if T1<sub>L</sub> > 0. In the latter case, the arm propulsion overlapped the leg insweep, and there was no glide.

The **effective leg insweep** (Ins<sub>eff</sub>) was the time between the extension and joining of the legs, except if T1<sub>L</sub> > 0. In the latter case, arm propulsion overlapped leg propulsion, and there was no leg insweep.

In each trial, each stroke phase was expressed as a percentage of a complete leg stroke (itself calculated from the mean of three leg strokes that were representative of the imposed swim pace. The effective duration of a complete stroke (100% of the time) corresponded to the sum of effective propulsion, effective recovery, effective glide and effective leg insweep, added to T2 and/or T3 when they were < 0, and to T1<sub>L</sub> when it was > 0.

**Statistical analysis**

All variables are presented as mean ± standard deviation in Table 1. The differences between the three trials for each variable were studied by ANOVA (Statview, Abacus Concepts, 1999) and completed by a PLSD Fisher test. The level of significance was set at 0.05.

<table>
<thead>
<tr>
<th>Time</th>
<th>V200</th>
<th>V100</th>
<th>V50</th>
</tr>
</thead>
<tbody>
<tr>
<td>Velocity (m·s&lt;sup&gt;-1&lt;/sup&gt;)</td>
<td>1.26±0.12&lt;sup&gt;b&lt;/sup&gt;</td>
<td>1.33±0.12&lt;sup&gt;b&lt;/sup&gt;</td>
<td>1.37±0.13&lt;sup&gt;b&lt;/sup&gt;</td>
</tr>
<tr>
<td>Stroke rate (stroke·min&lt;sup&gt;-1&lt;/sup&gt;)</td>
<td>33.1±5.3&lt;sup&gt;a,b&lt;/sup&gt;</td>
<td>39.29±6.4&lt;sup&gt;c&lt;/sup&gt;</td>
<td>47.35±8&lt;sup&gt;c&lt;/sup&gt;</td>
</tr>
<tr>
<td>Stroke length (m·stroke&lt;sup&gt;-1&lt;/sup&gt;)</td>
<td>2.26±0.37&lt;sup&gt;a,b&lt;/sup&gt;</td>
<td>2±0.3&lt;sup&gt;c&lt;/sup&gt;</td>
<td>1.7±0.23&lt;sup&gt;c&lt;/sup&gt;</td>
</tr>
<tr>
<td>Prop up limbs (%)</td>
<td>24.1±6.3&lt;sup&gt;b&lt;/sup&gt;</td>
<td>27.3±6</td>
<td>29.6±5.7</td>
</tr>
<tr>
<td>Arm propulsion (%)</td>
<td>18.2±4.2&lt;sup&gt;b&lt;/sup&gt;</td>
<td>20.5±4.4</td>
<td>22.9±6.2</td>
</tr>
<tr>
<td>Elbow push (%)</td>
<td>5.9±5.2</td>
<td>6.8±2.8</td>
<td>6.6±1.6</td>
</tr>
<tr>
<td>Arm glide (%)</td>
<td>53.5±8.8&lt;sup&gt;b&lt;/sup&gt;</td>
<td>48.12±7.8</td>
<td>42.5±7.8</td>
</tr>
<tr>
<td>Arm recovery (%)</td>
<td>22.3±4.4&lt;sup&gt;b&lt;/sup&gt;</td>
<td>24.5±4.7</td>
<td>27.7±5.4</td>
</tr>
<tr>
<td>1/2 arm rec (%)</td>
<td>10.6±3.1&lt;sup&gt;b&lt;/sup&gt;</td>
<td>12.1±3.7</td>
<td>14.1±4.5</td>
</tr>
<tr>
<td>2/2 arm rec (%)</td>
<td>11.6±3.6</td>
<td>12.5±4.5</td>
<td>13.7±4.8</td>
</tr>
<tr>
<td>Leg propulsion (%)</td>
<td>14.2±4.1&lt;sup&gt;b&lt;/sup&gt;</td>
<td>16.5±5.3</td>
<td>17.6±4.2</td>
</tr>
<tr>
<td>Leg insweep (%)</td>
<td>10.2±3.6</td>
<td>10.9±3.8</td>
<td>11.5±4.1</td>
</tr>
<tr>
<td>Leg glide (%)</td>
<td>50.8±8.3&lt;sup&gt;b&lt;/sup&gt;</td>
<td>46.2±6.8</td>
<td>41.4±5.9</td>
</tr>
<tr>
<td>Leg recovery (%)</td>
<td>24.6±6.5&lt;sup&gt;b&lt;/sup&gt;</td>
<td>26.3±4.6</td>
<td>29.4±6.3</td>
</tr>
<tr>
<td>1 1/2 leg rec (%)</td>
<td>12.8±4.5</td>
<td>13.3±3.6</td>
<td>14.7±4</td>
</tr>
<tr>
<td>2 1/2 leg rec (%)</td>
<td>11.8±2.9&lt;sup&gt;b&lt;/sup&gt;</td>
<td>12.9±2.9</td>
<td>14.6±3.7</td>
</tr>
<tr>
<td>T1&lt;sub&gt;L&lt;/sub&gt; (%)</td>
<td>−36.1±6.8&lt;sup&gt;b&lt;/sup&gt;</td>
<td>−29.3±6.3&lt;sup&gt;c&lt;/sup&gt;</td>
<td>−22.0±6</td>
</tr>
<tr>
<td>T1&lt;sub&gt;L&lt;/sub&gt; (%)</td>
<td>−25.8±7.6&lt;sup&gt;b&lt;/sup&gt;</td>
<td>−18.4±7.4&lt;sup&gt;c&lt;/sup&gt;</td>
<td>−10.4±7.8</td>
</tr>
<tr>
<td>T2 (%)</td>
<td>1.9±5.3</td>
<td>1.9±2.9</td>
<td>2.3±1.8</td>
</tr>
<tr>
<td>T3 (%)</td>
<td>4.6±5.7</td>
<td>3.7±5.5</td>
<td>4.1±6.3</td>
</tr>
<tr>
<td>T4 (%)</td>
<td>4.2±3.2</td>
<td>3.3±4.2</td>
<td>3.1±5.6</td>
</tr>
<tr>
<td>Prop&lt;sub&gt;eff&lt;/sub&gt; (%)</td>
<td>36.1±6.5&lt;sup&gt;a,b&lt;/sup&gt;</td>
<td>41.2±8.2</td>
<td>45.1±7.4</td>
</tr>
<tr>
<td>Ins&lt;sub&gt;eff&lt;/sub&gt; (%)</td>
<td>10.2±3.6</td>
<td>10.9±3.8</td>
<td>11.5±4.1</td>
</tr>
<tr>
<td>Gli&lt;sub&gt;eff&lt;/sub&gt; (%)</td>
<td>25.1±9.1&lt;sup&gt;a,b&lt;/sup&gt;</td>
<td>17.2±9.1&lt;sup&gt;c&lt;/sup&gt;</td>
<td>10.4±7.7</td>
</tr>
<tr>
<td>Rec&lt;sub&gt;eff&lt;/sub&gt; (%)</td>
<td>26.7±5.5</td>
<td>28.3±5.1</td>
<td>31.6±5.9</td>
</tr>
</tbody>
</table>

* difference between V200 and V100; † difference between V200 and V50; ‡ difference between V100 and V50; p < 0.05
Results

This study confirmed several significant differences between spatio-temporal variables, arm and leg stroke phases, and arm-leg coordination variables, as presented in Table 1. Significant correlations between variables are directly discussed in the Discussion section.

Velocity (V), stroke rate (SR), and stroke length (SL) (Fig. 4)

Arm and leg stroke phases

Propulsion of the upper limbs, arm propulsion, the first part of the arm recovery, arm recovery, leg propulsion, the second part of the recovery, and leg recovery all increased between V200 and V50 (p < 0.05). Arm and leg glide decreased between V200 and V50 (p < 0.05) and the elbow push and leg insweep remained stable (Figs. 5 and 6).

Arm-leg coordination

At all paces, T1_a and T1_b decreased (p < 0.05), indicating the decrease in effective glide (Fig. 7).

T2, T3 and T4 did not change significantly with the increase in pace. Nevertheless, considering the standard deviation of these values (Table 1), they were near zero and indicated high continuity in the arm and leg actions and, therefore, a mechanically correct coordination.

Effective stroke phases

The effective propulsion (Prop_eff) increased with each pace (p < 0.05), effective recovery (Rec_eff) increased between V200 and V50 (p < 0.05), and effective glide (Gle_eff) decreased with each pace (p < 0.05), while effective leg insweep remained stable (Ins_eff) (Fig. 8).

Discussion

Velocity (V), stroke rate (SR), and stroke length (SL)

At all paces, velocity, stroke rate, and stroke length varied in the same proportion as reported in other studies using the same methods to investigate the same level of expertise [5, 6, 10, 18, 24]. Only the breaststroke, in comparison with the other strokes, showed smaller SL at V100 than at V200 [5]. This could be due to the underwater recovery, which opposes greater forward active drag [11, 12, 25].
Arm and leg stroke phases

Upper limb propulsion increased with velocity [6] and, since the elbow push did not change, this reflected greater arm propulsion. Van Tilborgh et al. [27] showed that a high force peak during this phase results in very high body acceleration. The elbow push is an important phase, when the hands overcome the backward motion of the arm insweep and begin moving forward for the recovery. To be propulsive, this phase requires that the elbows be squeezed downward and inward and not simply dropped back against the ribs [15].

Leg propulsion also increased with velocity [6,24], providing the highest peak force [16,27] and the greatest body acceleration [9,11,25,30]. The leg insweep remained stable throughout the paces, so this phase was not a factor in the coordination changes.

Over the paces, arm and leg glides thus progressively decreased in favor of the propulsive phase. In fact, the high velocities of the sprint cause the greatest active drag. To overcome this, swimmers have to increase the propulsive phase. At V200, swimming opposed less active drag and velocity was lower; the swimmers thus favoured a streamlined position and used a long glide phase to maintain their mean velocity. Chollet et al. [6], Craig et al. [9], and Soares et al. [24] found similar results but used a different calculation of the glide phase, which is addressed in the discussion of effective glide.

The arm and leg recoveries increased significantly only between the two extreme velocities (V200 vs. V50), as reported by Chollet et al. [6]. Conversely, Soares et al. [24] showed stable leg recovery and decreased arm recovery, probably because their methodology was different. Thus, the longer arm recovery could be explained by the need to catch the water before the arms are pulled out. Without this catch preparation, the swimmer will slip through the water. Some swimmers used an overwater arm recovery, described as an “inefficient propulsive solution” by Villas-Boas and Santos [29] because it involves too many small speed fluctuations related to the trunk drag and a higher energy expenditure [28]. The longer leg recovery can be explained by the drag created by the hip flexion [27]. Since active drag increased with velocity, leg recovery slowed down propulsion more at the higher velocities. Arm recovery, just like leg recovery, had to occur with maximally streamlined movements [11], confirming the importance of good technique in active drag [14].

Fig. 7  Comparison of time gaps at various paces. T1a: End of leg propulsion – beginning of arm propulsion; T1b: End of leg insweep – beginning of arm propulsion; T2: Beginning of arm recovery – beginning of leg recovery; T3: End of arm recovery – end of leg recovery; T4: 90° arm flexion during recovery – 90° leg flexion during recovery; *a: difference between V200 and V100; *b: between V200 and V50; *c: between V100 and V50; p < 0.05.

Fig. 8  Comparison of effective stroke phases at various paces.
since the recovery phase of one pair of limbs could be overlapped by a propulsive phase of the other pair, it is perhaps more interesting to discuss the effective duration of recovery, propulsion and glide, and the time gaps measuring the possible phase overlaps, than the recovery of each pair of limbs.

**Arm-leg coordination and effective stroke phases**

The analysis of arm-leg coordination showed the steady spatio-time relationship between arm and leg movements for T2, T3, T4 (measuring arm-leg recovery coordination) and a change in T1\(_b\) and T1\(_b\) (measuring the glide effect) when the pace increased. These results were consistent with those of Chollet and Boulesteix [3] for the butterfly, indicating that the two strokes (butterfly and breaststroke) have a similar organisation of arm-leg coordination and similar coordination changes with increasing velocity.

From V200 to V50, the time gap T1\(_b\) was divided by 2.4, which implies that the effective glide became shorter by the same ratio. Regarding the standard deviation, T1\(_b\) at V50 could be near 0 (± 10.46 ± 7.8 %), which indicated the absence of glide and therefore a relative mechanical continuity between arm and leg actions (Fig. 9: arm-leg coordination of the 2003 French 50 m champion, European medallist and World finalist in the 100 m race). Craig et al. [9] showed that when the stroke rate increased progressively, the duration of the first deceleration (“time from the maximal velocity associated with the leg action to the minimal velocity before the arm action”) decreased because the arm action began earlier. In fact, Manley and Atha [16] suggested that the arms have a “reserve capacity” of time to move faster or not; they therefore can “reduce the duration of the leg-arm transitional phase”. Conversely, the legs do not have this reserve capacity because, at the end of their recovery, they are not in a streamlined position, unlike the arms that are extended forward. In this position, the arms either wait for the beginning of propulsion or anticipate it, thus explaining this “reserve capacity” of time.

T1\(_b\) was not positive, however, indicating that the glide decrease had no impact on leg insweep. Only some subjects overlapped arm propulsion with leg insweep, but on average, the swimmers did not reduce the glide enough to overlap them. They waited to be in a streamlined position (legs joined), corresponding to a biomechanical solution, to begin arm propulsion.

In conclusion, between V200 and V50, the adaptation of arm-leg coordination resulted from an increased effective propulsion associated with a decreased effective glide (Fig. 9), according to...
Tourny et al. [25] who showed a correlation of 77% to 86% between these two phases. This confirmed that the independent action of the two pairs of motor limbs (arm and leg propulsion increases in relation to arm and leg glide decreases) had a joint effect on body propulsion. In fact, the earlier arm action was responsible for both the effective propulsion increase and the effective glide decrease (in accordance with Craig et al. [9]).

T2, T3 and T4 showed no significant change at any pace, indicating the relative stability of the arm and leg recovery coordination ([3] in butterfly). Conversely, Craig et al. [9] showed a slower recovery (“second deceleration”) and a steady state of the acceleration phases with a faster pace. They expressed the duration of each phase in seconds (an absolute value), whereas our study expressed the effective phase as a percentage of a complete leg stroke (a relative value). Thus, in our study the effective recovery increase (the difference between V200 and V50) seems more related to changes in both effective propulsion and effective glide than to recovery organisation. Had Craig et al. [9] expressed their results in relative values, they most likely would have found the same results.

Furthermore, T2, T3 and T4 and their standard deviations (less than 5 ± 5%) were near zero, indicating relative synchronisation between the key points that identify the arm and leg phases. A relative continuity of action occurred between the negative (recovery) and positive (propulsive) phases. On the other hand, the recovery organisation was stable, showing relative synchronisation between the beginning of recovery, the flexion at 90°, and the end of the arm and leg recoveries.

When T2 and T3 were negative (for the highest standard deviation of T values), propulsive and negative (recovery) phases overlapped. A negative T2 value meant that the beginning of leg recovery overlapped the end of arm propulsion. This did not seem to be an effective biomechanical strategy because the propulsive phase was reduced to give place to a drag phase, whereas swimmers should reduce the negative phases [12]. Conversely, even if a negative T3 meant the overlap of two contradictory phases, it could be an effective sprint strategy to anticipate the beginning of leg propulsion without waiting for the end of arm recovery (Fig. 9). In fact, this superposition coordination was used by the top swimmers to increase their mean velocity, because waiting for the end of arm recovery to adopt a streamlined position did not help them to maintain a high mean velocity.

**Conclusion**

In the breaststroke, switching from V200 to V50 was associated with increased stroke rate, decreased stroke length, a change in the arm and leg phases, and a change in the arm and leg coordination and the effective phases. At a faster pace, the proportional increase in arm and leg propulsion was associated with a proportional decrease in arm and leg glide. Thus, at V200, the swimmers maintained their mean velocity by privileging a streamlined position and a more effective glide; this was not effective in sprint, where they had to increase their effective propulsion and decrease their effective glide.

This study measured the time gaps between the arm and leg phases and introduced a new method of characterising the arm-leg coordination in the flat breaststroke. The decrease in T12 and T13 (which measured the effective glide) when the pace was faster confirmed the shorter effective glide to achieve greater continuity of the arm and leg propulsive phases.

Furthermore, at each pace, the low T2, T3 and T4 values (measuring arm and leg recovery coordination) showed the strong synchronisation of the key points that identify the arm and leg phases, and suggested better coordination at the mechanical level (at slow velocity, beginning the action of one pair of limbs when the other one was in a streamlined position; at high velocity, continuity or overlap between propulsive and recovery phases; in all cases, synchronised recoveries) than at the motor level (end of the action of one pair of limbs synchronised with the beginning of the action of the other pair).

Time gaps thus appear to be a good measure of the swimmer’s skill at adapting his or her arm-leg coordination to biomechanical constraints.

**References**

5. Chollet D, Pelayo P, Tourny C, Sidney M. Comparative analysis of 100 m and 200 m events in the four strokes in top level swimmers. J Hum Mov Studies 1996; 31: 25 – 37