Arm coordination symmetry and breathing effect in front crawl

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Abstract

This study analysed the relationships among arm coordination symmetry, motor laterality and breathing laterality during a 100-m front crawl, as a function of expertise. Ten elite swimmers (G1), 10 mid-level swimmers (G2), and 8 non-expert swimmers (G3) composed three skill groups, which were distinguished by velocity, stroke rate, stroke length, breathing frequency (BF) and the mean number of strokes between two breaths – the stroke breath (SB) – over a 100-m front crawl. Four stroke phases were identified by video analysis (catch, pull, push and recovery) and the index of coordination (IdC) measured the lag time between the propulsive phases of the two arms. The three modes of coordination are catch-up (IdC < 0%), opposition (IdC = 0%) and superposition (IdC > 0%). The IdC was established as the mean of IdC1 and IdC2, which measured the lag time between the propulsive phases of the left and right arms, respectively. The coordination symmetry was analysed by comparing IdC1 and IdC2, and the breathing effect was studied by distinguishing IdC1 (and IdC2) with and without breathing. Motor laterality was determined by an adaptation of the Edinburgh Handedness Inventory. Breathing laterality was determined by a questionnaire and observation during the 100-m trial.

Most of the front crawl swimmers showed asymmetric arm coordination, with propulsive discontinuity on one side and propulsive superposition on the other. This asymmetry was most often related to breathing laterality (a preferential breathing side for a unilateral breathing pattern) and motor laterality (arm dominance), with different profiles noted. More than the breathing laterality itself, the breathing actions of the non-expert swimmers amplified their
asymmetric coordination on the breathing side. Conversely, the elite swimmers, who had higher and more stable spatial–temporal parameters (velocity and stroke lengths), a high coordination value (IdC) and lower breathing frequency (BF), managed their race better than the less proficient swimmers and their asymmetric arm coordination was not disturbed by breathing actions. By determining the dominant arm and the preferential breathing side, the coach can obtain a swimmer profile that allows both coach and swimmer to better understand and respond to excessive coordination asymmetry.

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1. Introduction

Expert swim performance depends on a high stroke rate and great stroke length, and thus an optimal stroke rate/stroke length ratio, with stroke length considered the most discriminative parameter of velocity (Arellano, Brown, Cappaert, & Nelson, 1994; Chollet, Pelayo, Delaplace, Tourny, & Sidney, 1997; Kennedy, Brown, Chengalur, & Nelson, 1990; Pai, Hay, & Wilson, 1984; Pelayo, Sidney, Kerifi, Chollet, & Tourny, 1996). The 100-m event, with its very high velocity, particularly requires stable and high stroke rate and stroke length throughout the race (Chollet et al., 1997; Sidney, Delhaye, Bailion, & Pelayo, 1999).

In 1971, Vaday and Nemessuri showed that the organisation of the arm stroke phases determines technical efficacy. Several recent studies have emphasized the close relationships among arm coordination, velocity and expertise (Chatard, Collomp, Maglischo, & Maglischo, 1990; Chollet, Chalies, & Chatard, 2000; Costill, Maglischo, & Richardson, 1992; Lerda, Cardelli, & Chollet, 2001; Seifert, Boulesteix, Carter, & Chollet, 2005; Seifert, Boulesteix, & Chollet, 2004). Chollet et al. (2000) developed the index of coordination (IdC) and demonstrated that elite swimmers had greater arm continuity in the sprint and in fact employed a relative opposition–superposition coordination (IdC > 0%). Less proficient swimmers, on the other hand, presented a lag time between the propulsions of the two arms and relied on catch-up coordination (IdC < 0%). Active drag increases with velocity irrespective of the swimmer’s expertise (Toussaint et al., 1988); however, elite sprinters are able to minimize this increase in active drag with increasing velocity (Kolmogorov & Duplishcheva, 1992; Kolmogorov, Rumyantseva, Gordon, & Cappaert, 1997).

Loetz, Reischle, and Schmitt (1988) first suggested the importance of understanding the interactions of arm coordination, leg kicks, and the body roll during arm strokes and breathing. In the front crawl, Hay, Liu, and Andrews (1993), Liu, Hay, and Andrews (1993), Payton, Hay, and Mullen (1997), and Yanai (2001) demonstrated how the body roll influences hand speed and the hand path. Payton et al. (1997) showed that a modest increase in the roll produced greater medio-lateral hand motion and hand speed, thus augmenting the hand’s potential to develop propulsive forces. Rolling must nevertheless be performed appropriately so that a
hydrodynamic and streamlined body position is maintained. Yanai (2001) therefore advised using the lowest stroke rate appropriate to achieve a specified speed to maintain the magnitude of the body roll. Obviously, a greater stroke length is needed to ensure the optimal stroke rate/stroke length ratio. The highly efficient patterns in elite swimmers are related to their symmetric body roll and hence to their more streamlined body position (Cappaert, Pease, & Troup, 1995), whereas non-experts show opposite rotations about the longitudinal axis of the body (Cappaert et al., 1995), suggesting that the control of their body roll is ineffective.

Several studies have analysed hand speed and the propulsive forces and noted an asymmetric pulling pattern at certain skill levels (Keskinen, 1994; Maglischo et al., 1988; Rushall, Holt, Sprigings, & Cappaert, 1994; Yeater, Martin, White, & Gilson, 1981). Kinetic and kinematic asymmetries were observed, although the researchers did not determine whether they were related to motor control deficits, strategy, limb dominance or external constraints (breathing, for example). In a study of swim bench exercise, however, Potts, Chralton, and Smith (2002) observed that the swimmers who used a bilateral breathing pattern appeared to have a more equally distributed external power output than the unilateral breathers, who seemed predisposed to less symmetric stroke action. An asymmetric power pattern between the lower limbs has been observed in walking, suggesting that the dominant limb has a propulsive function and the non-dominant limb has a role in the support and control of locomotion (Sadeghi, Allard, & Duhaime, 1997; Sadeghi, Allard, Prince, & Labelle, 2000). Recently, Sadeghi (2003) described a local asymmetry in the lower limbs that was compensated by globally symmetric behaviour when the totality of the limbs was considered. It thus may be that the dominant limb assumes a role of compensation (Gundersen et al., 1989; Sadeghi, Allard, & Duhaime, 2001) or guidance during movement.

Cardelli, Lerda, and Chollet (2000) studied the durations of exhalation, inhalation and inhalatory apnea. Longer inhalations were noted at high speed in the non-expert swimmers, leading to the suggestion that breathing may affect arm coordination (Lerda & Cardelli, 2003; Lerda et al., 2001). Swimmers in fact roll further when taking a breath (Payton, Bartlett, Baltzopoulos, & Coombs, 1999), although this greater roll with breathing does not interfere with the stroke parameters of elite swimmers (Payton et al., 1999). According to these authors, the elite swimmers maintain the same deep and wide hand path.

The preceding works suggest two lines of questioning: (1) Is symmetry in swim coordination related to expertise and, if so, do symmetric arm actions indicate good technique? (2) If not, does an asymmetric arm pattern emerge from internal properties (functional pathology, dominance of one arm) or in response to external constraints (breathing)? And what is the direction of causality: Is the asymmetric pattern determined by unilateral breathing? Or, conversely, does an asymmetry due to arm dominance lead to unilateral breathing?

Although arm coordination and the breathing-coordination relationship have been explored in the front crawl, no study has focused on the symmetry of arm actions and the effect of breathing actions and motor and breathing lateralities on this symmetry. The first aim of this study was to analyse the relationships among arm
coordination symmetry, arm dominance and preferential breathing side in a 100-m front crawl. It was hypothesised that different profiles would emerge: arm coordination in the front crawl would likely be asymmetric at all skill levels, due to both a preferred breathing side and a dominant arm. Other profiles of coordination asymmetry would be related to either breathing laterality or motor laterality. The coordination symmetry profile would be linked to bilateral breathing and/or mixed arm dominance. Secondly, we hypothesised that the less proficient swimmers’ unbalanced management of the 100-m (revealed by velocity, stroke rate, stroke length, and breathing frequency) and their poorer technique (stroke phase organisation) would disturb their breathing actions and thus further amplify their asymmetric arm coordination.

2. Methods

2.1. Subjects

Twenty-eight French swimmers provided informed written consent to participate in the study, which was approved by the University ethics committee. They constituted three skill groups (Table 1) ranging from an average school level to international ranking. Skill was assessed from a 100-m sprint in front crawl performed during the competitive season and expressed in percentage of the world record. Two Junior European Champions in 2002 and two World Champion medalists in 2003 composed the best group (G1), which was a national sprint group (near 90% of WR). The mid-level group (G2) comprised regionally ranked swimmers (near 80% of WR), and the lowest group (G3) had a level adequate for the Faculty of Sports Sciences (near 70% of WR). According to the criteria of Yanai and Hay (2000), none of the swimmers had shoulder injury and thus we assumed that coordination asymmetry would not be due to impingement. The one-way ANOVA (group) showed a difference in expertise among groups (Table 1).

Table 1
Anthropometric and expertise characteristics of the three swim groups

<table>
<thead>
<tr>
<th>Group</th>
<th>Number</th>
<th>Age (year)</th>
<th>Mass (kg)</th>
<th>Height (cm)</th>
<th>Arm span (cm)</th>
<th>Time on 100-m (s)</th>
<th>Expertise % of world record</th>
</tr>
</thead>
<tbody>
<tr>
<td>G1: Elite men</td>
<td>10</td>
<td>20.1 ± 3.3</td>
<td>77.4 ± 6.3</td>
<td>183.5 ± 5.8</td>
<td>189.8 ± 11.4</td>
<td>52.34 ± 2.52</td>
<td>90.1 ± 4.2</td>
</tr>
<tr>
<td>G2: Mid-level men</td>
<td>10</td>
<td>20.7 ± 1.4</td>
<td>72.4 ± 6.7</td>
<td>178.6 ± 6.9</td>
<td>183.4 ± 9.1</td>
<td>58.76 ± 1.18 a</td>
<td>79.6 ± 1.6 a</td>
</tr>
<tr>
<td>G3: Non-expert men</td>
<td>8</td>
<td>20.2 ± 1.6</td>
<td>70.4 ± 6.7</td>
<td>179.4 ± 7.1</td>
<td>184.6 ± 9.8</td>
<td>67.25 ± 3.07 a b</td>
<td>69.6 ± 3.1 a b</td>
</tr>
</tbody>
</table>

a: Significant difference with preceding group, b: with G1, p < 0.01.
2.2. Swim trials

In a 25-m pool, each swimmer dived and performed a 100-m crawl individually to avoid reliance on racing strategies and the influence of other swimmers on swim-trial management. For each swimmer, the best time this season was used to estimate the skill level. The reliability of the test was verified by comparison between the current best time in competition and the time achieved in the test.

2.3. Video analysis and spatial–temporal parameters (velocity, stroke rate, stroke length)

Two underwater video cameras (Sony compact FCB-EX10L) with rapid shutter speed (1/1000 s) were used at 50 Hz. Each camera was fixed on a trolley which ran along the side of the pool to ensure filming of the swimmers. One camera filmed the swimmer from a right-side view, the other from a left-side view. The trolleys were pulled by operators at the same velocity as the swimmers, with each subject’s head being the mark followed by the operators to control parallax. The cameras were connected to a double-entry audio–visual mixer, a video recorder and a monitoring screen to mix the right and left lateral views on the same screen, in accordance with the protocol of Chollet et al. (2000). A video timer was incrusted in the mixer to synchronise these two views.

A third camera, mixed with the right-side view for time synchronisation, filmed the 100-m of each swimmer in profile from above the pool. This aerial view enabled us to have the entire length of the pool on the video screen. Four bollards delimited the five 5-m zones constituting each 25-m length, as described in a thorough study of elite sprint swimmers (Seifert et al., 2005). The swimmer’s head delimited the entry and exit of the middle 15-m of each length, which was used to calculate the velocity (m s\(^{-1}\)). The mean stroke rate (stroke min\(^{-1}\)) was calculated from the underwater videos for 6–10 strokes of the middle 15-m swim zone. The calculation of the mean stroke length (m stroke\(^{-1}\)) was based on these values of velocity and mean stroke rate (stroke length = 60*velocity/stroke rate).

2.4. Arm coordination

Arm coordination was quantified using the index of coordination (IdC) defined by Chollet et al. (2000). Based on the two mixed underwater views, each arm movement was broken down into four phases and analysed by three different operators with a blind technique (Fig. 1). This enabled us to duplicate the subjective measurements of each key point, because each operator conducted his analysis without knowing the analyses of the other two operators. Then, the three analyses were compared. When the difference between the three video analyses did not exceed an error of 4/100 s, the mean of the three analyses was accepted to validate the key point of each phase. When the error exceeded 4/100 s, the three operators together proceeded to a new assessment of the phase key point.
Phase A: entry and catch of the hand in the water. This was the time between the hand’s water entry and the beginning of its backward movement.

Phase B: pull. This was the time between the beginning of the hand’s backward movement and its arrival into the plane vertical to the shoulder. This second phase was the initial part of propulsion.

Phase C: push. This was the time between the hand’s position below the shoulder to its exit from the water.

Phase D: recovery. This was the time between the hand’s exit from the water and its re-entry.

The duration of each phase was measured for each stroke with a precision of 0.02 s (50 Hz) and was expressed as a percentage of the duration of a complete stroke. The duration of the propulsive phases was the sum of phases B and C, and for the non-propulsive phases the sum of phases A and D. The duration of a complete stroke was the sum of the propulsive and non-propulsive phases.

The lag time between the beginning of propulsion in the first right arm stroke and the end of propulsion in the first left arm stroke defined IdC1 (i.e. arm coordination to the left side), which was expressed as a percentage of the duration of a complete stroke. The lag time between the beginning of propulsion in the second left arm stroke and the end of propulsion in the first right arm stroke defined IdC2 (i.e. arm coordination to the right side), which was also expressed as a percentage of the duration of a complete stroke (Fig. 1).

IdC was thus the mean of IdC1 + IdC2. A lag time between the propulsive phases of the two arms indicated “catch-up” coordination (IdC < 0%). When the propulsive phase of one arm started at the time the other arm finished its propulsive phase, the coordination was “opposition” (IdC = 0%). When the propulsive phases of the two arms overlapped, the coordination was “superposition” (IdC > 0%) (for more methodological details, see Chollet et al., 2000).

2.5. Arm to leg coordination

In line with the work of Chollet et al. (2000) and Millet, Chollet, Chalies, and Chatard (2002), the arm to leg coordination was assessed by the quantitative analysis of the leg kicks. The leg kick can be broken down into two movements: the downbeat and the
upbeat, which are identified from the high and low break points of the foot. Persyn, Daly, Vervaecke, Van Tilborgh, and Verhetsel (1983) distinguished two-, four-, and six-beat kicks, and suggested that swimmers principally use the last one in sprint races. For the six-beat, Maglishco (2003) noted that each downbeat of the legs is coordinated with one of the three arm sweeps of an underwater arm stroke. For example, if we take a right arm stroke, we see that the downsweep of that arm is coordinated with the downbeat of the right leg. Next, the insweep of the right arm is accompanied by the downbeat of the left leg, and last, another downbeat of the right leg occurs during the upsweep of the right arm. This timing is similar during the left arm stroke.

2.6. Coordination symmetry

The coordination symmetry was assessed by comparing IdC1 and IdC2. For example, an IdC = 0% can be obtained by IdC1 = 0% and IdC2 = 0%, indicating perfect symmetry. However, if IdC1 = −4% and IdC2 = +4%, IdC will also equal 0%, but in this case the coordination is asymmetric. Fig. 1 shows the case of an asymmetric coordination with a lag time on the left (IdC1 = −5.8%) and a superposition of actions on the right (IdC2 = +12.5%). The calculation of arm coordination and the assessment of its symmetry were based on 6–10 strokes swum in the middle 15-m zone of the pool length; that is to say, nearly 30 strokes per 100-m.

2.7. Breathing laterality

The breathing laterality was defined as the preferential breathing side and was established by a questionnaire:

- breathing side and breathing frequency during sprint competition (50-m),
- breathing side and breathing frequency during short competitive events (100-m, 200-m),
- breathing side and breathing frequency during long competitive events (400-m, 800-m, 1500-m),
- breathing side and breathing frequency during heavy-workload training,
- breathing side and breathing frequency during light-workload training.

We determined whether the swimmers used unilateral breathing (right or left) with a breathing frequency of two or four movements or bilateral breathing (breathing every three arm movements or breathing to the right side after two movements, then breathing after three movements, then breathing to the left side after two movements, etc.). Finally, the breathing laterality determined by the questionnaire was compared to the preferential breathing side observed during the swim trial.

2.8. Effect of breathing on the coordination symmetry

The breathing effect on coordination symmetry was explored by comparing IdC1 and IdC2 “with” and “without” breathing. When the swimmer turned his head to
the left side to breathe, this was termed IdC1 “with breathing”; when the head was turned to the right side, this was termed IdC2 “with breathing”. Hence, for each stroke, IdC1 and IdC2 were qualified as either “with” or “without” breathing. During the 100-m, all swimmers breathed every four and/or two arm movements to their preferential side (except the bilateral group). Therefore, for 6–10 strokes swum in the 15-m central zone of each 25-m length, 3–5 movements with breathing were compared with 3–5 movements without breathing.

2.9. Breathing parameters

The breathing frequency (BF) (breaths min$^{-1}$) was defined as the number of times the head turned to the side to breathe within the 15-m central zone, divided by the time taken to swim the 15-m, multiplied by 60 (Cardelli, Chollet, & Lerda, 1999). The stroke breath (SB) (stroke rate/BF ratio) was the mean number of strokes between two breaths calculated within the 15-m central zone (Cardelli et al., 1999).

2.10. Motor laterality

Arm dominance was determined by a laterality questionnaire adapted from the Edinburgh Handedness Inventory (Olfield, 1971). Based on the method of Annett (1970) and Olfield (1971), right, left or mixed arm dominance was determined.

2.11. Statistical analysis

When a normal distribution (Ryan Joiner test) and the homogeneity of variance (Bartlett test) were verified, parametric statistics were used; if not, non-parametric tests were used (Minitab 13.20, Minitab Inc., 2000).

2.11.1. Spatial–temporal parameters, stroke phases, arm coordination and breathing parameters

The comparisons among the three groups were performed using two-way ANOVAs [group (3 levels: G1, G2, G3) × length (4 levels: L1, L2, L3, L4)] for velocity, stroke rate, stroke length, entry phase (A), pull phase (B), push phase (C), recovery phase (D), propulsive phase, non-propulsive phase, IdC, the breathing frequency (BF) and SB. One-way ANOVAs (group) were then performed on the mean of the 100-m for each variable and completed by post hoc Tukey tests (Table 2). Finally, one-way ANOVAs (length) were performed for each variable and for each group and completed by post hoc Tukey tests (Table 2).

2.11.2. Coordination symmetry

2.11.2.1. Breathing laterality. For all swimmers, the breathing side used in the trial corresponded to the breathing side indicated in the questionnaire by the swimmer (Table 5). Therefore, three groups could be constituted: 15 subjects composed the right-side breathing group (4 of G1, 5 of G2, and 6 of G3) ($n = 489$), 10 subjects composed the left-side breathing group (5 of G1, 4 of G2, and 1 of G3) ($n = 321$), and 3
Table 2
Differences in the spatial–temporal parameters, the arm coordination and the breathing parameters among the three groups for the 100-m mean and for each length

<table>
<thead>
<tr>
<th>Groups</th>
<th>Length</th>
<th>Velocity (m s(^{-1}))</th>
<th>Stroke rate (stroke min(^{-1}))</th>
<th>Stroke length (m stroke(^{-1}))</th>
<th>Breathing frequency (BF) (breaths min(^{-1}))</th>
<th>Stroke breath (SB) (SR/BF ratio)</th>
<th>IdC (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>G1 (n = 10)</td>
<td>L1</td>
<td>1.87 ± 0.15</td>
<td>51.8 ± 2.8</td>
<td>2.17 ± 0.18</td>
<td>25.1 ± 6</td>
<td>2.19 ± 0.58</td>
<td>5.5 ± 3.5</td>
</tr>
<tr>
<td></td>
<td>L2</td>
<td>1.74 ± 0.09</td>
<td>46.8 ± 2.2 c</td>
<td>2.24 ± 0.12</td>
<td>34.4 ± 13.1 c</td>
<td>1.59 ± 0.75 c</td>
<td>3 ± 4 a</td>
</tr>
<tr>
<td></td>
<td>L3</td>
<td>1.62 ± 0.11 c d</td>
<td>44.4 ± 2.7 c d</td>
<td>2.2 ± 0.16</td>
<td>39.3 ± 9.5 d</td>
<td>1.18 ± 0.28 d</td>
<td>3.7 ± 3.6 d</td>
</tr>
<tr>
<td></td>
<td>L4</td>
<td>1.61 ± 0.1 d e</td>
<td>43.7 ± 2.4 d e</td>
<td>2.21 ± 0.17</td>
<td>37.1 ± 9 d</td>
<td>1.25 ± 0.33 d</td>
<td>3.5 ± 3.9 d</td>
</tr>
<tr>
<td></td>
<td>Mean</td>
<td>1.71 ± 0.16</td>
<td>46.5 ± 4</td>
<td>2.21 ± 0.16</td>
<td>33.9 ± 10.2</td>
<td>1.55 ± 0.64</td>
<td>3.8 ± 3.8</td>
</tr>
<tr>
<td>G2 (n = 10)</td>
<td>L1</td>
<td>1.7 ± 0.12 a</td>
<td>50.3 ± 3.5</td>
<td>2.04 ± 0.14 a</td>
<td>26.1 ± 10.1 a</td>
<td>2.13 ± 0.75 a</td>
<td>0.5 ± 3.9 a</td>
</tr>
<tr>
<td></td>
<td>L2</td>
<td>1.57 ± 0.1 a c</td>
<td>47.5 ± 2.9 c</td>
<td>1.99 ± 0.16 a</td>
<td>35.4 ± 6.7 c</td>
<td>1.38 ± 0.3 c</td>
<td>0.3 ± 3.7 a</td>
</tr>
<tr>
<td></td>
<td>L3</td>
<td>1.47 ± 0.1 a c d</td>
<td>45.6 ± 3.1 c d</td>
<td>1.95 ± 0.16 a d</td>
<td>43.6 ± 8.6 a c d</td>
<td>1.09 ± 0.34 a d</td>
<td>1.5 ± 4.4 a</td>
</tr>
<tr>
<td></td>
<td>L4</td>
<td>1.44 ± 0.12 a d e</td>
<td>44.7 ± 3.4 d e</td>
<td>1.95 ± 0.21 a d</td>
<td>42.8 ± 8.2 d</td>
<td>1.09 ± 0.33 d</td>
<td>3.2 ± 4.2 c d e</td>
</tr>
<tr>
<td></td>
<td>Mean</td>
<td>1.54 ± 0.15 a d e</td>
<td>46.8 ± 3.8</td>
<td>1.98 ± 0.17 a d</td>
<td>37.3 ± 10.7 a</td>
<td>1.41 ± 0.61 a</td>
<td>1.4 ± 4.2 a</td>
</tr>
<tr>
<td>G3 (n = 8)</td>
<td>L1</td>
<td>1.56 ± 0.17 a b</td>
<td>47.6 ± 3.5 a b</td>
<td>1.98 ± 0.2 b</td>
<td>35.2 ± 13.2</td>
<td>1.55 ± 0.67</td>
<td>0 ± 3.8 b</td>
</tr>
<tr>
<td></td>
<td>L2</td>
<td>1.42 ± 0.12 a b c</td>
<td>43.1 ± 2.6 a b c</td>
<td>1.97 ± 0.15 b</td>
<td>39.7 ± 12.8</td>
<td>1.19 ± 0.41</td>
<td>-1.2 ± 4.2 a b</td>
</tr>
<tr>
<td></td>
<td>L3</td>
<td>1.34 ± 0.11 a b c d</td>
<td>42.3 ± 2.3 a b d</td>
<td>1.9 ± 0.18 b c d</td>
<td>47.1 ± 7.6 d</td>
<td>0.91 ± 0.14 d</td>
<td>-0.7 ± 4.3 a b</td>
</tr>
<tr>
<td></td>
<td>L4</td>
<td>1.26 ± 0.1 a b c d e</td>
<td>41.9 ± 1.8 a b d e</td>
<td>1.81 ± 0.16 b d e</td>
<td>42.6 ± 6.3 d</td>
<td>1 ± 0.18 d</td>
<td>1.1 ± 4.8 a b c</td>
</tr>
<tr>
<td></td>
<td>Mean</td>
<td>1.38 ± 0.16 a b</td>
<td>43.5 ± 3.4 a b</td>
<td>1.91 ± 0.18 b</td>
<td>41.2 ± 10.8 b</td>
<td>1.17 ± 0.46 b</td>
<td>0 ± 4.4 a b</td>
</tr>
</tbody>
</table>

a: Significant difference with preceding group, b: with G1, \(p < 0.05\).
c: Significant difference with preceding length, d: with L1, e: with L2, \(p < 0.05\).
subjects composed the bilateral breathing group (1 swimmer of each group) \((n = 98)\). For each group, \(n\) corresponds to the total strokes swum.

The difference between coordination to the left side (IdC1) and the right side (IdC2) was studied in relation to breathing laterality by one-way ANOVAs [breathing laterality (3 levels: right, left, bilateral)] and completed by post hoc Tukey tests (Table 3).

For the three skill levels (Table 3) composing the right-side breathing group, the left-side breathing group and the bilateral breathing group and for each skill level group (Fig. 2), the comparison between IdC1 and IdC2 was conducted using a paired \(t\)-test.

2.11.2.2. Motor laterality. The results of the EHI (Table 5) authorized the constitution of three groups: 19 subjects composed the right-arm dominance group (3 of G1, 3 of G2 and 2 of G3) \((n = 618)\), 8 subjects composed the left-arm dominance group (6 of G1, 7 of G2 and 6 of G3) \((n = 261)\), and 1 swimmer of G1 showed mixed dominance \((n = 29)\). For each group, \(n\) corresponded to the total strokes swum.

Table 3
Coordination symmetry and breathing laterality

<table>
<thead>
<tr>
<th>Breathing laterality</th>
<th>IdC1 (%)</th>
<th>IdC2 (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Right-side group</td>
<td>4.05 ± 6.3</td>
<td>−0.18 ± 5.5 c</td>
</tr>
<tr>
<td>Left-side group</td>
<td>0.6 ± 5.1 a</td>
<td>4.85 ± 5.1 a c</td>
</tr>
<tr>
<td>Bilateral group</td>
<td>−2.75 ± 5 a b</td>
<td>−2.52 ± 4.6 a b</td>
</tr>
</tbody>
</table>

IdC1: left coordination, IdC2: right coordination, a: significant difference with preceding group, b: with the right breathing group, c: significant difference between IdC1, \(p < 0.05\).

Fig. 2. Relationships between breathing laterality and arm coordination asymmetry: comparison between IdC1 and IdC2 for the three skill level groups.
The difference between coordination to the left side (IdC1) and the right side (IdC2) was studied in relation to motor laterality by one-way ANOVAs [motor laterality (3 levels: right, left, and mixed)] and completed by post hoc Tukey tests (Table 4).

For the three skill levels (Table 4) composing the right-arm dominance group, the left-arm dominance group and the mixed dominance group and for each skill level group (Fig. 3), the comparison between IdC1 and IdC2 was made using a paired t-test, in accordance with the statistical analysis of Sadeghi et al. (1997, 2000).

2.11.2.3. Relationships between breathing laterality and motor laterality. Table 5 presents the two groups that could be constituted: 17 subjects displayed asymmetric coordination on the side of preferential breathing and arm dominance and composed the laterality group, while 8 swimmers had a mixed profile and composed the mixed group. The absolute difference between IdC1 and IdC2 was compared between the laterality and mixed groups by the non-parametric Kruskal–Wallis test [group: 2 levels (laterality, mixed)].

Table 4
Coordination symmetry and motor laterality

<table>
<thead>
<tr>
<th>Motor laterality</th>
<th>IdC1 (%)</th>
<th>IdC2 (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Right dominance group</td>
<td>2.98 ± 5.9</td>
<td>1.05 ± 5.1 c</td>
</tr>
<tr>
<td>Left dominance group</td>
<td>0.28 ± 6.6% a</td>
<td>2.35 ± 7.5 a c</td>
</tr>
<tr>
<td>Mixed dominance group</td>
<td>−0.35 ± 3% a</td>
<td>−1.26 ± 3.3 a</td>
</tr>
</tbody>
</table>

IdC1: left coordination, IdC2: right coordination, a: significant difference with preceding group, b: with the right breathing group, c: significant difference between IdC1, p < 0.05.

Fig. 3. Relationships between motor laterality and arm coordination asymmetry: comparison between IdC1 and IdC2 for the three skill level groups.
2.11.3. Effect of breathing on coordination symmetry

The breathing effect on coordination symmetry was analysed for each breathing group (for the whole group and for each skill level group) by studying the differences between \( n = 213 \) with and without breathing and the differences between \( n = 468 \) and without breathing from the 100-m mean, using a paired \( t \)-test (Fig. 4). During the 100-m, all swimmers breathed every four and/or two arm movements to their preferential side (except the bilateral group). Therefore, for 6–10 strokes swum within the 15-m central zone of each 25-m length,

<table>
<thead>
<tr>
<th>Breathing laterality (questionnaire and race observation)</th>
<th>Motor laterality (EHI)</th>
<th>Side of arm coordination asymmetry (IdC1/IdC2)</th>
<th>Number of swimmers</th>
</tr>
</thead>
<tbody>
<tr>
<td>Right</td>
<td>Right</td>
<td>Right</td>
<td>12</td>
</tr>
<tr>
<td>Right</td>
<td>Right</td>
<td>Left</td>
<td>2</td>
</tr>
<tr>
<td>Right</td>
<td>Left</td>
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</tr>
<tr>
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<td>Left</td>
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<tr>
<td>Left</td>
<td>Left</td>
<td>Left</td>
<td>5</td>
</tr>
<tr>
<td>Left</td>
<td>Left</td>
<td>Right</td>
<td>1</td>
</tr>
<tr>
<td>Left</td>
<td>Right</td>
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<td>1</td>
</tr>
<tr>
<td>Left</td>
<td>Right</td>
<td>Left</td>
<td>3</td>
</tr>
<tr>
<td>Bilateral</td>
<td>Right</td>
<td>Symmetric</td>
<td>1</td>
</tr>
<tr>
<td>Bilateral</td>
<td>Left</td>
<td>Symmetric</td>
<td>1</td>
</tr>
<tr>
<td>Bilateral</td>
<td>Mixed</td>
<td>Symmetric</td>
<td>1</td>
</tr>
</tbody>
</table>

Fig. 4. Effect of breathing on arm coordination (IdC1 and IdC2, with and without breathing) for the three groups.
3–5 movements with breathing were compared to 3–5 movements without breathing. Thus, \( n \) corresponds to the number of strokes with and without breathing for the whole population.

For all tests, the level of significance was set at 0.05.

3. Results

3.1. Spatial–temporal parameters

The two-way ANOVAs (group × length) showed that velocity, stroke rate and stroke length changed with expertise and the parts of the trial (respectively, \( F_{6,896} = 4.7, F_{6,896} = 5.4, F_{6,896} = 5.7 \), all \( p < 0.05 \)). For the 100-m mean and for each length, the one-way ANOVA (group) showed that velocity (\( F_{2,896} = 530, p < 0.05 \)), stroke rate (\( F_{2,896} = 123.2, p < 0.05 \)) and stroke length (\( F_{2,896} = 232.4, p < 0.05 \)) were higher with greater expertise (Table 2).

For G1 and G2, velocity and stroke rate decreased between the first and second lengths, but no difference was noted in the second half of the trial. The least expert swimmers (G3) decreased velocity throughout the 100-m and showed the same change in stroke rate as G1 and G2. The stroke length did not change for G1; it was greatest in the first length for G2 and decreased throughout the 100-m for G3 (Table 2).

3.2. Breathing parameters

For the 100-m mean and for each length, the one-way ANOVAs (group) showed that breathing frequency (BF) decreased with increased expertise (\( F_{2,896} = 5.1, p < 0.05 \)). The stroke rate/BF ratio, or the “stroke breath” (SB), which is the number of arm movements between each breath, increased with expertise (\( F_{2,896} = 6.1, p < 0.05 \)) (Table 2).

3.3. Arm coordination and stroke phases

The two-way ANOVAs (group × length) showed that IdC changed with expertise and the parts of the trial (\( F_{6,896} = 4.1, p < 0.05 \)). For the 100-m mean and for each length, the one-way ANOVAs (group) indicated that IdC increased with increased expertise (\( F_{2,896} = 69.6, p < 0.05 \)) (Table 2). The IdC of the most expert swimmers (G1) did not change over the 100-m, except in the first length where the diving start generated a higher IdC. Conversely, G2 and G3 showed increased IdC during the two last lengths of the trial (Table 2).

The two-way ANOVAs (group × length) showed that these coordination changes were due to differences in the organisation of the stroke phases (for catch phase: \( F_{6,896} = 2.4 \), for pull phase: \( F_{6,896} = 2.8 \), for push phase: \( F_{6,896} = 3.4 \), and for propulsive and non-propulsive phases: \( F_{6,896} = 4.2 \); all \( p < 0.05 \)). For the 100-m mean and for each length, the one-way ANOVAs (group) revealed that the relative duration of the catch phase decreased (\( F_{2,896} = 118.2, p < 0.05 \)) and the pull (\( F_{2,896} = 147.8\),
propulsive phase was longer \( (F_{2,896} = 77.6, p < 0.05) \) and the non-propulsive phase was shorter \( (F_{2,896} = 75.2, p < 0.05) \) for the most expert swimmers. Their stroke phases changed during the 100-m, particularly between the first length and the other lengths, which may have been due to the absence of fatigue at the beginning of the race. At the first length, the catch phase was shorter \( (p < 0.05) \) and the pull and push phases were longer \( (p < 0.05) \). Conversely, for G2 and G3, the pull and push phases were longer at the end of the race (at the third and/or fourth lengths). However, the longer propulsive phase of G2 and G3 was not effective, because stroke length decreased at the end of the trial, suggesting that the swimmers’ hands slipped through the water instead of propelling.

3.4. Arm to leg coordination

For the leg kicks, we observed that 6 downward movements were performed for one stroke of the two arms in all three groups. Our analysis confirmed that the arm to leg coordination conformed to the pattern described previously by Maglishco (2003). This coordination pattern continued throughout the entire 100-m (turn-in, turn-out and swimming parts), indicating that the whole population used a six-beat kick.

3.5. Coordination symmetry

3.5.1. Breathing laterality

For left coordination (IdC1) and right coordination (IdC2), the one-way ANOVAs (breathing laterality) showed significant differences (respectively, \( F_{2,905} = 72.9 \) and \( F_{2,905} = 117.7; \) both \( p < 0.05 \)) among the right-side, left-side and bilateral breathing groups, suggesting that coordination was more affected on the preferential breathing side (Table 3). Indeed, IdC1 was smaller for the left-side group than for the right-side group, indicating that breathing laterality caused a discontinuity between the propulsive actions. The paired \( t \)-test established differences between IdC1 and IdC2 for the right \( (T_{957} = 11.2, p < 0.05) \) and the left \( (T_{639} = -10.6, p < 0.05) \) breathing groups, whatever the skill level (Table 3).

For each skill level, Fig. 2 shows that the right- and left-side breathing groups displayed asymmetric coordination, whereas the bilateral group showed a symmetry between the arm actions. It should be recalled that this last group was represented by one swimmer from each skill level.

3.5.2. Motor laterality

For left coordination (IdC1) and right coordination (IdC2), the one-way ANOVAs (motor laterality) showed significant differences (respectively, \( F_{2,905} = 20.4 \) and \( F_{2,905} = 7.5; \) \( p < 0.05 \)) between the right-arm, left-arm and mixed dominance groups, suggesting that coordination was more affected on the side of the dominant arm (Table 4). IdC1 was smaller for the left dominance group than for the right dominance group, indicating that motor laterality played a role in the asymmetric
coordination. The paired *t*-test established differences between IdC1 and IdC2 for the right (*T* 1204 = 6.1, *p* < 0.05) and left (*T* 511 = −3.3, *p* < 0.05) dominance groups composed of the three skill levels (Table 4). The mixed dominance group (represented by only 1 swimmer of G1) presented symmetric coordination.

Regarding each skill level group, Fig. 3 shows that only the more expert swimmers (G1 and G2) had asymmetric coordination on the side of the dominant arm. Conversely, the non-experts (G3) in the right dominance group did not show coordination asymmetry and in the left dominance group they revealed asymmetric coordination opposite to the side of the dominance.

### 3.5.3. Relationships between breathing laterality and motor laterality

The Kruskal–Wallis test showed no significant difference in asymmetry between the laterality group (which had asymmetric coordination on the side of preferential breathing and the dominant arm) and the group with a mixed profile. This suggested that same-side motor and breathing lateralities did not lead to higher coordination asymmetry than mixed profiles.

### 3.6. Effect of breathing on the coordination symmetry

The paired *t*-tests of IdC1 and IdC2, with and without breathing, showed that for the whole population, IdC1 with breathing (1.13 ± 4.7%) was smaller than IdC1 without breathing (2.39 ± 6.6%) (*T* 487 = 3.1, *p* < 0.05) and IdC2 with breathing (0 ± 6.3%) was smaller than IdC2 without breathing (2.78 ± 5.1%) (*T* 888 = 7.3, *p* < 0.05).

IdC1 with breathing was smaller than IdC1 without breathing for the mid-level group (G2) (*T* 184 = 2.4, *p* < 0.05) and the non-expert swimmers (G3) (*T* 149 = 3.1, *p* < 0.05) (Fig. 4). Similarly, IdC2 with breathing was smaller than IdC2 without breathing for the mid-level group (G2) (*T* 231 = 2.9, *p* < 0.05) and the non-expert swimmers (G3) (*T* 288 = 7.7, *p* < 0.05) (Fig. 4).

### 4. Discussion

#### 4.1. Coordination symmetry

##### 4.1.1. Asymmetry and breathing laterality

Recently, Lerda and Cardelli (2003) and Lerda et al. (2001) compared the coordination between the breathing-side arm and the non-breathing-side arm in mid-level swimmers. Their subjects showed greater discontinuity in the arm actions linked to breathing, but the coordination asymmetry was not analysed to determine what part was due to breathing and what part was due to asymmetric motor organisation in propelling. Their study nevertheless suggested the interest of analysing arm coordination in relation to the breathing side.

The results of our study (Table 3, Fig. 2) suggested that the preferential breathing side defined a breathing laterality that influenced the symmetry of arm coordination.
Although some coaches teach bilateral breathing patterns, unilateral breathing is most often used in competition and then tends to generalise to training sessions. A preferential side of breathing may also be learned, and with repetition it becomes a motor automatism. By consistently turning the head to the same side to inhale, swimmers stabilise this automatism and develop a breathing laterality that causes a lag time between the propulsive actions of the two arms (Cardelli et al., 2000; Lerda & Cardelli, 2003). Indeed, the left- and right-side breathing groups both showed a smaller IdC on the breathing side than on the other side, which confirmed the relationships between the unilateral breathing side and arm coordination asymmetry. These results agree with those of Yanai and Hay (2000), who noted longer stroke time on the breathing side. They thus concluded that unilateral breathing leads to asymmetry in the pulling pattern. Studying the arm power output in swim bench exercise, Potts et al. (2002) confirmed that unilateral breathers were predisposed to less symmetrical stroke action. Finally, the difference between IdC1 and IdC2 was noted in all three skill level groups (Fig. 2), suggesting that it was not related to expertise or deficits, but rather to a preferential breathing side.

In the bilateral breathing group, which was composed of one swimmer from each skill level, no arm asymmetry was noted. This may indicate that alternating the breathing side suppresses asymmetry. Yanai and Hay (2000), in fact, advised bilateral breathing to alternate the lateral trunk tilt, which is linked to breathing, in order to reduce the risk of shoulder impingement. However, although bilateral breathing may have enabled balanced propulsion by ensuring symmetric arm coordination, it did not lead to better propulsion. In fact, the observation of arm dominance led us to think that one arm is responsible for installing the swimming rhythm and probably produces the higher forces; this would explain why elite swimmers use unilateral breathing in competition.

4.1.2. Asymmetry and motor laterality

For the three skill groups combined (Table 4), the significant differences between IdC1 and IdC2 indicated longer gaps between the propulsive phases on the side of the dominant arm. This asymmetric coordination could result from motor laterality, which implies asymmetric pulling patterns between the arms, as observed by Rushall et al. (1994). Yeater et al. (1981) studied the swimming forces in the tethered front crawl and concluded that the two arms showed different peak forces. Keskinen (1994) measured velocity and force over a stroke cycle in a 10-m sprint and a 10-s tethered swim in 12 swimmers and found that the velocity and force during the push and pull phases changed between arms. The differences in velocity between the left and right arms during the pull phase ranged from 0.1 to 0.4 m s\(^{-1}\), indicating an asymmetric pattern.

No relationship between the side of asymmetry (i.e. catch-up coordination) and motor laterality was noted in the non-expert swimmers (G3) (Fig. 3), suggesting that the dominant arm shows motor adaptations as a function of expertise. Fig. 3 shows that the G3 swimmers had symmetric coordination or an asymmetry on the side opposite to the dominant arm; this indicates that the dominant arm did not guide propulsion, but instead guided the breathing actions (Lerda & Cardelli,
Conversely, the relationship between asymmetry and motor laterality in the more expert swimmers (G1 and G2) seemed to correspond to that noted in voluntary motor acts like walking (Sadeghi et al., 2000), where the mobilising or manipulating limb was found to be the preferred limb and the limb used to support the actions was the non-preferred limb. In swimming, the support function of the non-dominant arm may be linked to breathing.

4.1.3. Relationship between breathing laterality and motor laterality to explain coordination asymmetry

Table 5 shows that when breathing laterality and motor laterality were associated to analyse the coordination symmetry, different swimmer profiles emerged: (1) swimmers with the same side for coordination asymmetry, breathing and arm dominance composed the laterality group; (2) swimmers with the same side for motor and breathing laterality but the opposite side for coordination asymmetry composed the first part of the mixed group; (3) swimmers with the same side for coordination asymmetry and either motor laterality or breathing laterality composed the second part of the mixed group; and (4) swimmers showing coordination symmetry as the last group. Most of the swimmers (17 of 28 subjects, Table 5) were in the laterality group because they had the same side for coordination asymmetry, motor laterality and breathing laterality. This finding supports the notion that the dominant arm might have been the propulsive arm, while the non-dominant arm served as a support or a compensation, for unilateral breathers who had too great a body roll or too wide an insweep on one side. In other words, the non-dominant arm could serve to control local asymmetries in order to ensure globally balanced swimming (as shown in walking by Sadeghi, 2003). Studying the 1984 US Olympic swim team, Maglischo et al. (1988) observed different arm coordination patterns and stated that the swimmers had developed compensatory motor strategies, by combining stroke phases, to ensure effective forward propulsion.

This first profile is illustrated in Fig. 1 and shows the left-arm coordination asymmetry of the 2002 European Junior Champion in relation to his left preferential breathing side and his left-arm dominance. A superposition coordination appeared on the right side (IdC2 = +12.5%), whereas the coordination indicated a lag time on the left side (IdC1 = −5.8%). Nevertheless, the longer propulsive phase of the right arm (55.8% of a complete right-arm stroke) than of the left arm (49.5% of a complete left-arm stroke) did not prove that the right side was dominant, because a high mean force applied over a long period is not as effective as high peak forces during the push and/or pull phases (Maglischo et al., 1988; Toussaint & Beek, 1992). We hypothesise that the longer propulsive phase on the non-breathing side compensated for the breathing actions on the other side, where the relative propulsive phase was shorter. In fact, according to Lerda and Cardelli (2003), the push phase occurs during exhalation on the same side, enabling swimmers with unilateral breathing to associate propulsion and breathing. These authors noted that exhalation is short and explosive, and is associated with a dynamic push phase to produce high peak force. Thus, as observed in walking (Sadeghi et al., 2000), the dominant arm, in association with breathing to the same side, could be responsible for propulsion, particularly
since the push phase was synchronised with the expiration. Conversely, the non-dominant arm played the role of control and support to inhalation, particularly by efficiently catching the water with the arm extended in the front position.

On the other hand, as Table 5 shows, a swimmer with a left coordination asymmetry can have a mixed profile (left breathing side and right-arm dominance). In this case, unlike the 2002 European Junior Champion, the dominant arm was on the non-breathing side to boost the stroke rhythm after breathing. For this profile, the dominant arm would enable to increase the right and left arm continuity (longer propulsive duration) when the swimmer breaths on the non-breathing side.

Finally, no profile (laterality vs. mixed) showed greater arm coordination asymmetry than the others, which indicates that the swimmers used different compensatory motor strategies to balance the asymmetry of coordination (as previously advanced by Maglischo et al., 1988).

4.2. Effect of breathing on coordination symmetry

Although G1 showed differences between IdC1 and IdC2, the IdC1 with and without breathing did not differ (nor did IdC2 with and without breathing), indicating that breathing did not disturb the asymmetric coordination of these swimmers (Fig. 4). These results are in line with those of Payton et al. (1999), who studied arm stroke phases and the body roll during breathing and breath-holding and showed that elite swimmers could breathe without changing the width and depth of the stroke. Thus, as suggested by Sadeghi et al. (1997), the asymmetry of arm coordination is neither a mistake nor due to breathing actions. As previously suggested, it is instead the result of a motor laterality, and a breathing laterality stabilised by learning. As proposed by Rassler and Kohl (2000) regarding walking, the dominant arm in G1 controlled forward propulsion and installed a swim rhythm in relation to the breathing frequency, which would explain the coupling of the motor and breathing lateralities. In regard to walking, Rassler and Kohl (2000) concluded that energy cost is partly an effect of coordination and probably also due to a more precise regulation of the breathing pattern. Finally, unilateral breathing (due to breathing laterality) in expert swimmers may simply coincide with asymmetric arm coordination without amplifying it.

Conversely, for G2 and G3, the IdC1 with and without breathing differed (as did IdC2) (Fig. 4), indicating that breathing changed the arm coordination in the direction of greater catch-up (Lerda & Cardelli, 2003; Lerda et al., 2001). With breathing, IdC1 and IdC2 < 0% corresponded to catch-up, whereas without breathing, IdC1 and IdC2 > 0% revealed greater continuity in the arm propulsion, or a relative opposition–superposition coordination. In fact, during the 100-m swim, the less expert swimmers inhaled more frequently than the experts (Table 2), suggesting that the longer time spent with the head turned to the side was associated with decreased continuity in the arm actions (Cardelli et al., 2000; Lerda & Cardelli, 2003). This disturbance in the technique of the lower performers caused by breathing was also confirmed by Cappaert et al. (1995) in research on the body roll. These authors showed that the non-experts had difficulties in controlling their body roll because
they had an opposite rotation around the longitudinal body axis instead of the symmetrical body roll of the elites. Because of their greater control of the body roll, the elite swimmers maintained a more streamlined body position and a more efficient pulling pattern (Cappaert et al., 1995). Thus, as suggested by Cappaert et al. (1995), the expert swimmers (G1) managed to synchronise inhalation and propulsion without disturbing their arm coordination, whereas the less expert groups (G2 and G3) had an asymmetric coordination that was amplified by breathing. It thus may be that the unbalanced management of the 100-m trial (in terms of velocity, stroke rate, stroke length, breathing frequency) and the poorer technique (stroke phase organisation) of the lower performers disturbed their breathing actions and thereby amplified their arm coordination asymmetry.

4.3. Management of the race

The elite swimmers revealed better management of the trial by their higher spatial–temporal and coordination values, and a better control of their breathing frequency. The differences in velocity were principally explained by stroke rate and stroke length, with the elite men showing the highest values and a good stroke rate/stroke length ratio, in line with the findings of previous studies (Arellano et al., 1994; Chollet et al., 1997; Kennedy et al., 1990; Pai et al., 1984; Pelayo et al., 1996).

The inter-length comparisons showed that the elite swimmers (G1) were characterised by a stable stroke length throughout the race (according to Cardelli et al., 1999; Chollet et al., 1997) and a more stable velocity during the last two lengths, unlike G3, who tended to decrease velocity and stroke length throughout the 100-m. This confirmed that stroke length is the most discriminative parameter of velocity (Arellano et al., 1994; Chollet et al., 1997; Kennedy et al., 1990; Pai et al., 1984; Pelayo et al., 1996).

Concerning the coordination of arm movements and the stroke phase organisation, the smaller catch phase and greater pull and push phases of G1 in comparison with G2 and G3 indicated that high expertise and high velocity are signalled by a relatively longer propulsive phase and higher IdC (in accordance with Chollet et al., 2000; Keskinen & Komi, 1993; Lerda et al., 2001; Toussaint & Beek, 1992). Thus, G1 managed to maintain a high velocity by overlapping their arm propulsions with a high superposition (IdC > 0); whereas this superposition was smaller for G2, and G3 showed an opposition coordination (IdC = 0). As demonstrated by Seifert et al. (2005), the experts started swimming with a strong rhythm (at the first length) and then maintained stable stroke phase organisation, arm coordination, and stroke length for the rest of the race. Conversely, G2 and G3 started with a slower rhythm and then tended to sprint at the fourth length. They increased IdC and the relative duration of the propulsive phase, but this was ineffective because fatigue eventually caused them to decrease the stroke length. The video analysis revealed that the hand sweep slipped upward during the upsweep, instead of moving backward (Costill et al., 1992; Maglischo et al., 1988). Moreover, even though the relative duration of the propulsive phase was longest for the lowest performers, a high average force
is not as effective as a high maximal force (Maglischo et al., 1988; Toussaint & Beek, 1992).

Finally, as regards breathing frequency (BF) and stroke breath (SB), G1 showed a lower BF and a higher SB than G3 (in accordance with Cardelli et al., 1999). This was certainly the case for the first length, where better timing between the dive and swim start and a more streamlined position ensured a high velocity for G1 and enabled them to delay fatigue and breathe less often than G3 (Table 2). Because G3 had a poorer technique (ineffective superposition coordination and decrease in stroke length at the end of the race) than G1, they took 17 s more to complete the 100-m, which need a higher BF and a smaller SB. Town and Vanness (1990), in a study of three conditions of controlled frequency breathing, showed that the need to breathe either decreased the exercise intensity or increased the stroke rate, both being changes that indicate unbalanced race management (Chollet et al., 1997; Sidney et al., 1999). Therefore the poorer trial management of G2 and G3 was likely could cause their higher breathing frequency and could explain the increase in the asymmetry coordination when breathing.

Concerning the arm-to-leg coordination, the six-beat kick was used by all three groups throughout the entire 100-m (turn-in, turn-out and swimming parts), indicating that the change in arm coordination (IdC) and the arm coordination asymmetry of each group was not related to the leg kick, but rather to race management, breathing, fatigue and/or expertise.

4.4. Practical applications

The analysis of the relationships among arm coordination asymmetry and the sides of breathing and motor laterality revealed different profiles (Table 5). This information could be useful for balancing excessive asymmetry in the coordination. Indeed, by understanding the roles of the dominant arm and the preferred breathing side, the coach is better equipped to provide effective solutions to correct excessive arm asymmetry. For example, the coach can suggest that the swimmers modify the breathing frequency and/or the breathing side by adopting bilateral breathing (three-beat), a bilateral frequency (three-two-three-two beat), or breathing on the non-preferential side during easy training sessions, or even under heavy workloads.

5. Conclusion

Most of the front crawl swimmers had asymmetric arm coordination, with propulsive discontinuity on one side and propulsive superposition on the other. This coordination asymmetry was related to breathing laterality (preferential breathing side for a unilateral breathing pattern) and motor laterality (arm dominance), although different profiles emerged. Most showed a laterality profile (17 of 28 subjects): their dominant arm was on the preferential breathing side and may have had a predominant role in propulsion and the management of swimming rhythm. The non-dominant arm, which was on the non-breathing side, would have thus
supported propulsion and compensated the discontinuity caused by inhalation. The swimmers with a mixed profile (8 subjects) did not show less asymmetric coordination than the swimmers with a laterality profile; however, their dominant arm and preferential breathing side intervened differently in the support and compensation of propulsion. A third profile (3 subjects), which corresponded to symmetric arm coordination, coincided with bilateral breathing and was independent of expertise. This confirmed the relationship between unilateral breathing and coordination asymmetry, and suggests that coordination symmetry relates to both motor laterality and breathing laterality. The breathing actions (inhalation) of the less-expert swimmers (G2 and G3), more than breathing laterality, amplified their coordination asymmetry on the breathing side. With higher and more stable spatial–temporal parameters (velocity, stroke length), a high coordination value (IdC) and lower breathing frequency, the elite swimmers managed their trial better than the less expert swimmers, which suggests that their arm coordination asymmetry was not disturbed by breathing actions.

Finally, the investigation of the dominant arm and preferred breathing side could help both coach and swimmer to determine the swimmer’s profile and to intervene more rapidly and effectively to control excessive asymmetry in the arm coordination.

References


