Effect of Force Symmetry on Coordination in Crawl

Abstract

The relationship between breathing laterality and motor coordination symmetry as a function of the symmetry of medial rotator muscle force in the shoulders was investigated. The principal objective was to distinguish swimmer profiles. Thirteen expert male swimmers performed the front crawl and were assessed for: (i) inter-arm coordination with the IdC and arm coordination symmetry with the Symmetry Index, (ii) breathing laterality, and (iii) the symmetry of the isokinetic force in the shoulder medial rotators. The results indicated that the relative duration of catch+pul was greater for the dominant arm (51.7%) than for the non-dominant arm (48.4%) for the swimmers with force asymmetry (p < 0.05) and occurred on the side with the higher force (dominant arm). Two profiles were revealed: (i) swimmers for whom breathing laterality was related to force symmetry and stroke phase duration and (ii) swimmers for whom the impact of breathing laterality on force symmetry and stroke duration was low. The first profile corresponded to sprint specialists and the second profile corresponded more to middle-distance specialists.

Introduction

The front crawl is the fastest swim stroke and is often used for training. The front crawl is described as an alternating stroke because while one arm is propelling, the other is recovering. However, this alternation of arm actions does not ensure propulsion symmetry [1,11,15,39]; notably, several studies have analysed hand speed [11], hand path [1,15] and the propulsive forces [39] and noted an asymmetric pulling pattern at certain skill levels. Moreover, as regards the different breathing modes (unilateral vs. bilateral) usually adopted by the swimmers, asymmetrical arm coordination and power output could occur in the front crawl [23,31]. The coordination was compared between the breathing-side arm and the non-breathing side arm in mid-level swimmers and found that greater discontinuity in the arm action was linked to breathing [12,13]. It has further been suggested that turning the head to breathe increases the hydrodynamic drag experienced by the body [8,21]. Breathing causes a lateral movement, disturbing body alignment [13] (directly by the opposite arm action or indirectly by a compensatory action to re-establish balance), as well as the continuity of propulsive actions and the kinematics of the hand path through the water. These perturbations due to breathing were ampliﬁed to the non-preferential breathing side. Similarly, differences of hand speed patterns and strength have been identiﬁed during the successive phases of the stroke cycle between the dominant and non-dominant sides on the patterns [15,28,39]. Asymmetry may thus be a true coordination mode and not just a functional error [31]. Training volume and its intensiﬁcation to develop high swimming expertise have an impact on the swimmer’s musculoskeletal adaptations [18]. The demand placed on the shoulder’s medial rotator muscles is very high during the propulsive phase of the stroke cycle. Movement analysis during the crawl clearly shows the predominance of muscle work occurring at the anterior part of the shoulder [37,38]. The swimmer’s propulsion through water is accomplished by powerful movements of medial rotation and adduction. The electromyographic studies [29] revealed minimal activity by the supraspinatus and infraspinatus during free-style propulsion. In contrast, the pectoralis major and subscapularis, which
are both medial rotators and adductors, actively contributed to propulsive movement. A significant difference was recorded in the forces produced in medial rotation versus lateral rotation in swimmers [18]. The high repetition of arm swimming movements could thus cause hyper-development of the medial rotator muscles [2]. The forces generated by the internal rotator muscles of the shoulder are close to those generated by the water because in the catch phase the water is relatively stable. Thus, the water offers high resistance to the hand catch and the hand is unable to reach high speeds. This great resistance to hand entry into the water generates high forces in the medial rotators of expert swimmers. The higher the movement frequency, the greater the resistance will be [26].

Isokinetic methods are widely used to evaluate the force of the shoulder’s medial rotators. A review of the literature on rotator muscle evaluation indicates that peak forces are usually measured as they provide a good index of maximal muscle performance [9,27,35]. Shoulder medial and lateral rotation strength were tested and the calculated torque values obtained with a hand-held dynamometer were comparable to the isokinetic measurements, and the Masters’ level swimmers had symmetrical arm strength [16]. For the authors, the comparable values between the right and left arms were explained by the observation that swimming involves using the two arms simultaneously and in a symmetric manner. A methodological criticism can be raised regarding these studies of the impact of laterality in that, although the relationship between maximal muscle force and the performance of an activity requiring low technical skill is straightforward, the relationship when performance requires high technical skill is far less evident [32,34]. The evaluation of peak force will not give a complete picture when the forces being investigated result in great part from high technical skill. The peak torque is one instantaneous point in the curve (0.02 s) and it is not similar to the long and continued force applications that are closer to sports activities [33]. To evaluate the muscle force of swimmers’ shoulders, isokinetic measures thus seem better adapted to take into account the level of swimming expertise.

In fact, the continuity of motor force during the propulsive phase is a discriminating factor of swimming performance. The more continuous and overlapping propulsive movements make for a discriminating factor of swimming performance. The more continuous and overlapping propulsive movements make for a more effective use of propulsive force and probably account for the greater speeds attained [14].

The medial rotator muscle force measured at a maximal rotation angle was noted to best express the shoulder dynamics during the front crawl [37,38]. The evaluation of the asymmetry in medial rotator force calculated from the mean torques is thus an objective tool to investigate swim technique.

Some of the technical characteristics of front crawl swimmers, particularly regarding motor coordination, have been already demonstrated using an objective index: the Index of Coordination [5,30]. This index quantifies the spatial-temporal coordination of the phases of one arm in relation to those of the other arm. Yet, so far no study has examined the relationship between the collected data on inter-arm motor coordination in front crawl swimmers and the forces developed by the shoulder’s medial rotator muscles. The aim of this study was to identify the musculoskeletal characteristics of crawl swimmers with intensive practice. As these characteristics depend on the breathing side profiles and the symmetry of the arm coordination, it was important to distinguish the impact of force asymmetry from that of breathing laterality on the asymmetry of coordination.

Hypothesis 1 was that breathing laterality would have an impact on the symmetry of the medial rotator forces and the arm coordination of front crawl swimmers. Hypothesis 2 was that a profile would emerge, with the dominant arm control lateral to the preferred breathing side.

**Material and Methods**

**Participants**

Thirteen male swimmers performed a 100-m front crawl at maximal velocity. They provided informed written consent to participate in the study, which was approved by the University Ethics Committee. The subject characteristics and anthropometric measures were made using Winter’s [36] procedures (age 18.6±2.5 years; height 181.9±5.8 cm; mass 72.1±7.7 kg; and arm span 183.3±6.7 cm). Skill level was assessed from a 100-m sprint in front crawl performed during the competitive season: the mean ± SD time was 55.5±2.2 s (min. 51.17 s and max. 57.00 s), which corresponded to French national level. This time was then expressed as a percentage of the current world record: 84.3±3.3%. Two types of swimmers composed our population, sprinters and middle-distance specialists. None of the swimmers showed shoulder injury and we thus assumed that coordination asymmetry would not be due to impingement [37,38]. Last, none had pulmonary disease.

**Swimming test**

For each participant, the protocol imposed one simulation of the 100-m event over 25 m to avoid fatigue effects and isolate the effects of breathing habits due to laterality and learning. The swimmers in this study swam at a speed of 1.8 m·s⁻¹ over 100 m. They were given a swim time for the arms only, which was 60–85% of the swim time using both arms and legs: 1.45 m·s⁻¹. The swim time was: 8.3±0.1 s for 12.5 m. The performance values were as follows: mean velocity was 1.5±0.07 m·s⁻¹, and mean stroke length was 2.17±0.18 m·stroke⁻¹; mean stroke rate was 41.5±3.3 stroke·min⁻¹. The breathing constraint was one breath every four strokes to the preferential breathing side. The trial was self-paced and started in the water, without diving. A target time for the 25 m was based on a simulation time established during training sessions. After the test, all swimmers were informed of their performance, which was expected to be within ±2.5% of the target time. If the target time was not met, the subject repeated the test after a 4-min rest. The swimmers had their legs attached and used a pull-buoy to remove any influence of the legs on the inter-arm coordination.

**Video analysis**

Two underwater video cameras (Sony compact FCB-EX10L) with rapid shutter speed (1/1000 s) were used (50 Hz), each fixed on a trolley that ran alongside the pool. One camera filmed the swimmer from the right, the other from the left. The trolleys were pulled by an operator at the same velocity as the swimmers, with each swimmer’s head being the mark followed by the operator to control parallax. The cameras were connected to a double-entry audio-visual mixer, a video recorder and a monitoring screen to genlock and mix the right and the left lateral views on the same screen, from which the average stroke rate (from hand entry at the first stroke to hand entry at the second stroke) and the Index of Coordination (IdC) were calculated [5]. A video timer was incrusted in the mixer to synchronize and
genlock the two lateral views. An external side-view camera (50 Hz, Sony, TRV25), genlocked and mixed with the underwater right side-view camera, videotaped all trials of each swimmer from above the pool. This third camera measured the time over a distance of 10 m (from 10 m to 20 m) to obtain the clean velocity and stroke rate. Two plots delimited the 10 m and 20 m on the right and left sides of the swimming pool. When the head of the swimmer reached the rope line at 10 m and 20 m, respectively, time was recorded. The stroke rate was obtained by counting the requisite number of video frames for three strokes taken in the centre of the 10 m covered. The stroke length (SL) was calculated from the average velocity (V) and the stroke rate (SR); SL = VxSR/60.

Arm stroke phases
Each arm movement was broken down into four phases: 1) Entry and catch of the hand in the water: this phase corresponds to the time between the entry of the hand into the water and the beginning of its backward movement. 2) Pull: this phase corresponds to the time separating the beginning of the hand’s backward movement and its arrival in a plane vertical to the shoulder and constitutes the first part of propulsion. 3) Push: this phase corresponds to the time from the position of the hand below the shoulder to its release from the water and constitutes the second part of propulsion. 4) Recovery: this phase corresponds to the point of water release to water re-entry of the arm, i.e. the above-water phase. The average duration of each phase was measured with a precision of 0.02 s and was expressed as a percentage of the overall duration over three strokes taken in the 10-m central part of the 25 m. Three operators analysed the key points of each phase with a blind technique; that is, without knowing the analyses of the other two operators. The three analyses were compared only when each operator had completed his analysis. When the difference between the three video analyses did not exceed an error of 0.04 s, the mean of the three analyses 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 point.

The duration of the propulsive phase is the sum of the pull and push phases, and the duration of the non-propulsive phase is the sum of the entry and recovery phases.

Arm coordination symmetry
Two indexes of coordination (IdCleft; IdCright) enabled us to calculate the continuity between the propulsive actions of the two arms: IdCleft was defined as the time gap between the beginning of pull in the first right arm stroke and the end of push in the first left arm stroke; IdCright was defined as the time gap between the beginning of pull in the second left arm stroke and the end of push in the first right arm stroke [5]. IdCleft and IdCright were calculated for three strokes without breathing in the 10-m central part of the 25 m. The analysed strokes were those without breathing to assess breathing habits due to breathing laterality and learning and not due to breathing actions (head turning and inhalation).

When a lag time occurred between the propulsive phases of the two arms, the stroke coordination was called catch-up (IdC < 0%) [5]. When the propulsive phase of one arm started as the other arm ended its propulsive phase, the coordination was called ‘opposition’ (IdC = 0%). When the propulsive phases of the two arms overlapped, the coordination was called superposition (IdC > 0%).

The coordination symmetry was assessed by calculating the Symmetry Index (SI). This index was adapted from Robinson’s symmetry index [25], which was applied to walking. SI = |IdCleft−IdCright/0.5(IdCleft+IdCright)| × 100.

−10% < SI < 10% revealed symmetry while SI < −10% and SI > 10% indicated asymmetry [10]. In our case, −10% < SI < 10% revealed symmetry between the coordination of the right and left sides; SI < −10% indicated asymmetry to the left side; SI > 10% indicated asymmetry to the right side.

Breathing laterality
The breathing laterality was defined as the preferential breathing side and was established by 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) or bilateral breathing (breathing every three arm movements). Then, only swimmers using unilateral breathing patterns were included in our experiment.

Force symmetry: Identification of the dominant arm by measuring the isokinetic force of the shoulder’s medial rotator muscles
The rotator muscles were assessed isokinetically using a Kin Com® dynamometer (500 H, Chattecx Corp., Chattanooga, TN, USA). Each swimmer was seated and then stabilized in the chair with two crossed belts placed 30° from the lever arm for assessment in the scapular plane [6]. Each belt was fixed across the chest, from the shoulder and under the axilla. The subject’s back remained in contact with the chair throughout testing to minimize trunk movements. The subject was assessed with the arm in 90° abduction. The subject’s elbow was placed in a V-shaped elbow support and the resistance pad was adjusted just above the wrist. The hand was in pronation on the pad. The zero position of the lever arm corresponded to the horizontal line and was the same for all subjects. The full range of motion was 110°, from the vertical line (90°) to 20° under the horizontal line, and this did not change during the test. A value was not accepted if the subject did not apply force throughout the entire assessment test range of motion (ROM).

The procedure included three tests for each side. The side assessed first was random. Tests were performed at 90°.s⁻¹ and assessed the maximal strength of the medial rotators (MR) in concentric mode. Prior to testing, each subject performed a 10-min warm-up consisting of medial and lateral rotations of both shoulders using a rubber band. Ten submaximal (120°.s⁻¹) repetitions were performed in medial and lateral rotation. The subjects had 15 min of rest between tested sides.

The mean torque of the entire ROM had to be corrected to ensure an objective measure. The real time of isokinetic muscle work is not the same as the predetermined amplitude of work because the iso-acceleration and iso-deceleration phases affect the mean torque [6]. The ROM was thus reduced by 10° in the data analysis.

with the removal of the data affected by iso-acceleration (5°) and iso-deceleration (5°).

In the isokinetic data analysis, the mean torque was calculated from instantaneous torques from 85° to −15° of medial rotation. Average torque was expressed in Newton meters. The dominant arm was determined as the strongest arm as measured with the dynamometer.

The force symmetry was also assessed by calculating the Symmetry Index (SI):

\[ SI = \frac{\text{Arm dominant} - \text{Arm non-dominant}}{0.5(\text{Arm dominant} + \text{Arm non-dominant})} \times 100. \]

In accordance with Herzog et al. [10], −10% < SI < 10% revealed symmetry, while SI < −10% indicated asymmetry to the dominant arm and SI > 10% indicated asymmetry to the non-dominant arm.

The medial rotators are the muscles most used by front crawl swimmers for forward propulsion [17, 18], and these muscles are principally used during the catch and pull phases [37, 38], the relative durations of catch + pull of the dominant and non-dominant arms were compared.

Statistical analysis

All values are given as means ± SD. A normal distribution (Ryan Joiner test) and the homogeneity of variance (Bartlett test) were verified and thus authorized parametric statistics (Minitab 14.10, Minitab Inc., 2003). The difference in relative durations of catch + pull between the dominant arm and the non-dominant arm was analysed by two-way ANOVA [fixed factor: arm dominant vs. non-dominant; random factor: participants]. The level of significance was set at 0.05.

Results

The breathing laterality questionnaire showed that six swimmers preferred the right side for breathing and seven swimmers preferred the left side. Table 1 shows that all swimmers demonstrated coordination asymmetry and eight displayed force asymmetry. Table 2 summarizes the relationships among coordination asymmetry, force asymmetry and breathing laterality, indicating that (i) for 12 swimmers (all except S4), breathing laterality was to the same side as the coordination asymmetry and (ii) for eight swimmers (S1, S3, S4, S5, S8, S9, S11, S13), breathing laterality was opposite to the side of the force asymmetry.

Last, the ANOVA indicated that the relative duration of catch + pull was greater for the dominant arm (51.7%) than for the non-dominant arm (48.4%) for the swimmers with force asymmetry (p < 0.05). Notably, Table 3 shows that the greater relative duration of catch + pull occurred on the side with the higher force (dominant arm). Conversely, the swimmers with force symmetry showed a non-significant difference in the relative durations of catch + pull between the two arms.

Discussion

The aim of this study was to analyse the relationship between breathing laterality and motor coordination symmetry as a function of the symmetry of medial rotator muscle force in the shoulders.

Our results confirmed hypothesis 1 in that breathing laterality had an impact on the symmetry of the medial rotator forces and the arm coordination of front crawl swimmers. Regarding hypothesis 2, the data revealed two types of profile: (i) a profile...
of swimmers for whom breathing laterality seemed to be related to force symmetry and stroke phase duration and (ii) a profile of swimmers for whom the impact of breathing laterality was not in accordance with the force symmetry or stroke duration as these latter remained symmetric.

The isokinetic force measured on a dynamometer does not accurately reflect the situation of swimming, given that the swimmer’s position and angular velocity of movement are so specific. Nevertheless, the isokinetic dynamometer gives objective and valid data on medial rotator muscle force. The propelling phase of the freestyle stroke consists of shoulder medial rotation and adduction, as confirmed by EMG studies [22]. The front crawl is an overhead activity, and two specific characteristics have been demonstrated: (i) swimmers develop greater force in the medial rotators than do sedentary subjects and (ii) swimmers show a greater range of motion in the medial rotators than the range of 49° to 53° reported in sedentary groups [16, 19].

The shoulder joint soft tissue adaptation may be a response to specific demands. However, these adaptations could contribute to shoulder disorders.

In our study, given that the torque measured in the medial rotator muscles (measured with an isokinetic dynamometer) was highest during the catch and pull phases, it is particularly interesting to observe that for eight swimmers, the force asymmetry (assessed by the mean force) was related to the longer relative duration of medial rotator activity in these phases. After the external sweep in the stroke cycle, an internal sweep occurs, causing high forces to be developed in the medial rotators in association with the adductors [15, 24]. At the end of the arm recovery and the beginning of the catch phase, the arm was raised and hyper-extended, and the scapular belt and thorax were in a fixed position. During this phase, the medial rotator muscles were working in an isometric mode towards stabilization after the brutal end of the open kinetic chain, marked by contact with the water surface. The time spent in the two phases of catch and pull was greater for the arm opposite to the breathing side. Over the course of repeated crawl movements and years of training, this pattern might accentuate the force imbalance between the two arms. In the catch phase, the water is relatively stable and offers great resistance to the hand catch, which cannot achieve high speed.

The hand on the breathing side, even though it has a more rapid underwater path, will produce lower forces than those of the hand to the controlateral side. Swimmers thus create a longer period of propulsive force application, generating more power [4, 6, 14, 15, 26]. Moreover, breathing laterality, which is reinforced by learning and training, was strongly linked to force asymmetry and coordination asymmetry [3]. In particular in our study, the dominant arm, which spent more time extended forward, not only supported breathing but also led to coordination asymmetry, notably by causing catch-up coordination (i.e. propulsive discontinuity).

Over time, musculoskeletal transformations would lead to the following adaptation: if the stronger arm is on the side opposite to the breathing side, the motor action time of the medial rotators will be greater on the strong arm side. In this case, the duration of MR force has to be differentiated from the duration of propulsion (MR force time = catch + pull vs. propulsive time = pull + push). This would explain why no significant relationship was noted for this profile between MR force and the asymmetry of coordination, since IdC calculates only the ratio of propulsive phases to non-propulsive phases. This first profile corresponds to the sprint specialist.

Our results agree with those of the literature [17, 18, 37, 38] and underline the great medial rotation developed in the shoulder during the catch and pull phases. Moreover, the high position of the head in sprint swimmers amplifies the demand placed on the medial rotators and adductors of the shoulders.

The second profile of swimmers showed a symmetric pattern of force production, indicating that breathing laterality influenced only arm coordination and did not affect the motor action time of the medial rotator muscles. The force symmetry can be explained by the fact that these swimmers were not sprinters but middle-distance specialists and thus did not need to produce the same high forces for each stroke cycle. Closure of the open kinetic chain at the end of arm recovery is less brutal since these swimmers train and compete at lower stroke rates than sprinters [20]. The force symmetry can also be explained by the duration of catch + pull, which did not significantly differ between the right and left sides. The asymmetry of coordination was particularly noteworthy in the propulsive push phase, which would explain this asymmetry. In this case the dominant arm may not play the role of support but could guide the propulsion [31].

Swimmers who breathe bilaterally during submaximal exercise seem to have a better distribution of power between the right and left arms than those who use a unilateral pattern [23]. To prevent rotator cuff injury, bilateral breathing could be recommended for submaximal speeds, especially during training.

**Conclusion**

Although it is often assumed that the forces developed in the right and left arms during front crawl swimming are the same, it appears that unilateral breathing and the development of greater strength of the dominant arm lead to a differentiation in the swimmer’s arms. In the same swimmers, we assessed: (i) inter-arm coordination with the IdC and arm coordination symmetry

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**Table 3** Relative durations of the catch + pull phases of the dominant and non-dominant arms for two groups of swimmers: swimmers with force asymmetry and swimmers with force symmetry.

<table>
<thead>
<tr>
<th>Groups</th>
<th>Participants</th>
<th>Dominant Arm in %</th>
<th>Non-dominant Arm in %</th>
</tr>
</thead>
<tbody>
<tr>
<td>force asymmetry</td>
<td>S1</td>
<td>48.9</td>
<td>52.2</td>
</tr>
<tr>
<td></td>
<td>S3</td>
<td>59.2</td>
<td>52.8</td>
</tr>
<tr>
<td></td>
<td>S4</td>
<td>51.1</td>
<td>46</td>
</tr>
<tr>
<td></td>
<td>S5</td>
<td>48.4</td>
<td>45.9</td>
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<tr>
<td></td>
<td>S8</td>
<td>53.4</td>
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<tr>
<td></td>
<td>S9</td>
<td>52</td>
<td>49.8</td>
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<tr>
<td></td>
<td>S11</td>
<td>60.1</td>
<td>54.3</td>
</tr>
<tr>
<td></td>
<td>S13</td>
<td>40.4</td>
<td>38.3</td>
</tr>
<tr>
<td>mean</td>
<td></td>
<td>51.7 *</td>
<td>48.4</td>
</tr>
<tr>
<td>SD</td>
<td></td>
<td>5.9</td>
<td>4.8</td>
</tr>
<tr>
<td>force symmetry</td>
<td>S2</td>
<td>52.4</td>
<td>55.9</td>
</tr>
<tr>
<td></td>
<td>S6</td>
<td>49.7</td>
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<tr>
<td></td>
<td>S10</td>
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<td></td>
<td>S12</td>
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<tr>
<td>SD</td>
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<td>6.2</td>
<td>4.9</td>
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*significantly different with the non-dominant arm, p < 0.05*
with the Symmetry Index, (ii) breathing laterality and arm dominance, and (iii) internal rotator force symmetry. We then looked for relationships among these parameters. Two swimmer profiles emerged from our findings: (i) swimmers for whom breathing laterality seemed to relate force symmetry and stroke phase duration, and (ii) swimmers for whom the impact of breathing laterality was not in accordance with the force symmetry or stroke duration because these last remained symmetric. The distinction of these two profiles provides an indication of the swimmer’s technical skill and could orient training techniques to prevent instabilities of the shoulder joint.

References
3. Bruce M. Breathing, grabbing large breaths and exhaling slowly are keys to winning races. Swim Tech 1993; 29: 28–30