Influence of swimming speed on inter-arm coordination in competitive unilateral arm amputee front crawl swimmers

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A R T I C L E   I N F O

Article history:
Available online 30 August 2010

PsycINFO classification:
3290
3720

Keywords:
Swimming
Disability sport
Motor control
Biomechanics
Crawl

A B S T R A C T

This study examined the effect of swimming speed on inter-arm coordination and the inter-relationships between swimming speed, inter-arm coordination, and other stroke parameters, in a group of competitive unilateral arm amputee front crawl swimmers. Thirteen highly-trained swimmers were filmed underwater during a series of 25-m front crawl trials of increasing speed. Arm coordination for both arms was quantified using an adapted version of the Index of Coordination. Inter-arm coordination of the amputee swimmers did not change as swimming speed was increased up to maximum. Swimmers showed significantly more catch-up coordination of their affected-arm compared to their unaffected-arm. When sprinting, the fastest swimmers used higher stroke frequencies and less catch-up of their affected-arm than the slower swimmers. Unilateral arm-amputees used an asymmetrical strategy for coordinating their affected-arm relative to their unaffected-arm to maintain the stable repetition of their overall arm stroke cycle. When sprinting, the attainment of a high stroke frequency is influenced mainly by the length of time the affected-arm is held in a stationary position in front of the body before pulling. Reducing this time delay appears to be beneficial for successful swimming performance.

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0167-9457/$ - see front matter © 2010 Elsevier B.V. All rights reserved.
doi:10.1016/j.humov.2010.05.009
1. Introduction

Success in competitive swimming depends on a swimmer’s ability to maximize propulsion and minimize resistance. In able-bodied front crawl swimming, where the two arms move rhythmically in an anti-phase inter-limb relationship (Nikodelis, Kollias, & Hatzitaki, 2005), the hand plus forearm segment is seen as the major propelling surface responsible for about 85% of the total propulsion (Toussaint & Beek, 1992). Not all of the front crawl arm stroke action is propulsive however. The recovery, entry, and catch are recognized to be non-propulsive phases within the stroke cycle (Chollet, Chalies, & Chatard, 2000; Maglischo et al., 1988). When considering the effectiveness of a swimmer’s technique, understanding how the propulsive and non-propulsive phases of the two arms are coordinated is crucial.

An examination of the arm coordination of competitive front crawl swimmers with a disability has received much less attention from researchers than that given to able-bodied swimmers (e.g., Chollet et al., 2000; Nikodelis et al., 2005; Potdevin, Bril, Sidney, & Pelayo, 2006; Seifert, Chollet, & Bardy, 2004; Seifert, Chollet, & Rouard, 2007). Presently, only Satkunskiene, Schega, Kunze, Birzinyte, and Daly (2005) appear to have addressed this specific research area. Within a group of well-trained swimmers with diverse locomotor disabilities, these authors showed that swimmers across a range of impairment groups exhibited certain similarities with able-bodied swimmers. In particular, the “more-skilled” swimmers were characterized by their ability to overlap the propulsive phase of one arm with the propulsive phase of the other and attain higher stroke frequencies, when compared to “less-skilled” swimmers. It was acknowledged however that large variations existed between the disabled swimmers’ stroking techniques. These were attributed to the diverse functional impairments of the swimmers.

Competitive swimmers with a single, elbow-level amputation are clearly impaired when compared to able-bodied swimmers, as they are deprived of an important propelling surface (i.e., hand plus forearm segment). If these body segments are missing, swimmers must rely on the surface area of the existing limb to generate propulsion (Prins & Murata, 2008). Theoretically, it has been demonstrated that it is possible for the affected limb of a front crawl swimmer with a single elbow-level amputation to generate propulsion (Lecrivain, Slaouti, Payton, & Kennedy, 2008). In practice however, at swimming speeds higher than 1 m s\(^{-1}\), uncertainty remains as to whether the affected-arm of a unilateral arm amputee can contribute effectively to propulsion. Payton and Wilcox (2006) reported that for unilateral arm amputee swimmers, the increase in intra-cyclic swimming speed observed during the underwater pull of the affected-arm did not correlate with the shoulder extension velocity of the same arm. This suggests that factors other than limb speed, such as the coordination and trajectory of the underwater arm stroke action, may be more important in determining the effectiveness of the stroking technique.

For unilateral arm amputee front crawl swimmers, increases in swimming speed are achieved by increasing stroke frequency (Osborough, Payton, & Daly 2009). However, it is unclear how these swimmers change their inter-arm coordination over a range of swimming speeds. Osborough et al. (2009) also showed that when these swimmers sprint, stroke frequency is significantly related to swimming speed. Again it is unclear which of the various inter-arm coordination patterns adopted by this specific group of impaired swimmers (e.g., Osborough et al., 2009; Payton & Wilcox, 2006), is more conducive to attaining a successful sprinting performance.

This study examined the effect of swimming speed on inter-arm coordination and the inter-relationships between swimming speed, inter-arm coordination, and other stroke parameters, in a group of competitive unilateral arm amputee front crawl swimmers. It was hypothesized that the inter-arm coordination of the swimmers would change with a change in swimming speed and that when sprinting, the fastest swimmers would exhibit an inter-arm coordination style that would be related to stroke frequency and swimming speed.

2. Methods

2.1. Participants

Thirteen (3 male and 10 female) competitive swimmers (age 16.9 ± 3.1 years; height 1.69 ± 0.09 m; mass 63.6 ± 13.0 kg; mean ± SD), whose mean long course 50-m front crawl personal
best time was 32.7 ± 3.1 s, participated in this study. The best times of the three male participants were ranked between 24th and 30th in the world for the long course 50-m front crawl (International Paralympic Committee, 2008). For the same event, three of the female participants were ranked between 5th and 12th in the world and four were ranked between 38th and 45th in the world. The best times of the remaining three females were ranked outside the top 60 in the world.

All participants were single-arm amputees, at the level of the elbow. Twelve were congenital amputees and one received her amputation shortly after birth. Twelve of the swimmers competed in the International Paralympic Committee S9 classification for front crawl; one male swimmer competed in the S8 classification due to an additional impairment of one of his lower limbs. The procedure for the data collection was approved by the Institutional Ethics Committee. All participants provided written informed consent before taking part in the study.

2.2. Swim trials

After a standardized 600-m warm up each participant completed seven, self-paced 25-m front crawl trials, from a push start, at 3-min intervals. Seven of the swimmers performed the trials from slow to maximum swimming speed, the rest performed the trials from maximum to slow swimming speed. Participants were requested to swim each trial at a predetermined target pace, based on a percentage of their 50-m front crawl personal best time. All trials were manually recorded by two experienced timekeepers using chronograph stopwatches (Model 898). Any trial that was not close to the predetermined target pace (i.e., within ±2%) was repeated after a 3-min rest. To control for the effects of the breathing action on the swimming stroke, participants were instructed not to take a breath through a 10-m test section of the 25-m pool.

2.3. Video analysis

Two digital video camcorders (Panasonic NVDS33), sampling at 50 Hz with a shutter speed of 1/350 s were used to film the participants under the water, from opposite sides, over the 10-m test section of the pool (Fig. 1). Each of the camcorders was enclosed in a waterproof housing suspended underwater from one of two trolleys that ran along the side of the pool, parallel to the participants’ swimming direction. The field of view of each camcorder was adjusted so that the whole body of each participant was visible. To scale the recorded video footage a calibration rope, with markers every meter, was suspended horizontally in the water directly beneath the participant. Operators pulled the trolleys at the same speed as the participants, keeping the participant’s hip joint marker in the center of the field of view.

2.4. Data processing

The digital video footage was transferred to a laptop computer and analyzed using SIMI Motion 7.2 software (SIMI Reality Motion Systems GmbH, Unterschleißheim, Germany). Three consecutive, non-breathing stroke cycles (i.e., from the entry of the hand of the unaffected-arm to the fourth entry of that hand), for each participant, were selected for analysis. The estimated locations of the gleno-humeral joint center and the elbow joint center of both the affected- and unaffected-arms were digitized at 50 Hz to obtain the angular position of the upper-arms, as a function of time. Upper-arm angle was determined relative to the water surface. The latter was used to establish a true horizontal frame of reference. Before filming, the skin overlaying the joint centers was marked with black pen to help estimate their location.

2.5. Arm coordination and stroke phases

The Index of Coordination (IdC) is often used to quantify the arm coordination of able-bodied front crawl swimmers. The IdC, as described by Chollet et al. (2000), conforms to one of three major models: (1) Catch-up describes a time delay between the propulsive phases of the two arms (i.e., IdC < 0). (2)
Opposition describes a continuous series of propulsive actions: one arm begins the Pull phase when the other is finishing the Push phase (i.e., IdC = 0). (3) Superposition describes an overlap, to a greater or lesser extent, of the propulsive phases (i.e., IdC > 0).

While being a valuable measurement tool for able-bodied swimmers, problems arise when trying to apply the IdC to swimmers with a single elbow-level arm amputation. First, the IdC uses the hand positions of able-bodied swimmers to define four arm phases of the front crawl stroke cycle. The participants in this study however were missing a hand plus forearm segment. Second, the IdC assumes that an able-bodied swimmer generates propulsion during the Pull and Push phases of the arm stroke cycle. Currently, it is uncertain whether, and if so at what point, the affected-arm of a unilateral arm amputee can contribute effectively to propulsion. For these reasons, an adapted version of the Index of Coordination (IdCadapt), which used a common reference point on both arms rather than the onset of propulsion to quantify arm coordination, was utilized in this study. The arm stroke phases of the unilateral arm amputee swimmers were determined from the angle made by the shoulder-to-elbow position vector relative to the horizontal. Similar approaches have been used previously (e.g., Persyn, Hoeven, & Daly, 1979; Rouard & Billat, 1990).

Each upper-arm movement was divided into four phases (Fig. 2): Entry and Glide (A); Pull (B); Push (C); and Recovery (D).

(A) Entry and Glide: from where the elbow joint center entered the water (0°) to where the shoulder-to-elbow position vector made an angle of 25° with the horizontal. This latter position corresponded to a point where typically the swimmers actively initiated extension of their affected-arm.

(B) Pull: from the end of the Entry and Glide (25°) to where the shoulder-to-elbow position vector made an angle of 90° with the horizontal.

(C) Push: from the end of the Pull (90°) to where the shoulder-to-elbow position vector made an angle of 155° with the horizontal. This latter position corresponded to a point where, as a result of the rolling action of the swimmers’ trunk and the bow-wave created by the swimmers’ movement through the water, the most-distal part of the swimmers’ affected-arm typically exited the water.
(D) *Recovery*: from the end of the Push (155°) to where the elbow joint center enters the water (360°).

It should be noted that the start of the Pull phase and end of the Push phase, as described above, did not necessarily correspond to the start and end of propulsion.

The time duration of each phase was determined with a precision of 0.02 s from the video recordings, calculated as a mean of three arm stroke cycles. The duration of a complete arm stroke cycle was defined as the sum of the four phases ($A + B + C + D$). Each phase was then expressed as a percentage of the duration of the complete arm stroke cycle.

The arm coordination for both the affected ($I_{dc_{af}}$) and unaffected ($I_{dc_{un}}$) limbs was determined at 80%, 85%, 90%, 95%, and 100% of each participant’s maximum swimming speed ($SS_{max}$). These percentages were determined from the predetermined target-paced swims and, where the trials did not exactly match, by linear interpolation of the two adjacent experimental data points. The lag time between the beginning of the Pull phase with the affected-arm and the end of the Push phase with the unaffected-arm defined $I_{dc_{af}}$ (i.e., arm coordination on the affected side), which was expressed as a percentage of the duration of the complete arm stroke cycle. The lag time between the beginning of the Pull phase of the unaffected-arm and the end of the Push phase with the affected-arm defined $I_{dc_{un}}$ (i.e., arm coordination on the unaffected side), which was expressed as a percentage of the duration of the complete arm stroke cycle.

$I_{dc_{adapt}}$ (%) was the mean of $I_{dc_{af}}$ (%) and $I_{dc_{un}}$ (%). A time delay between the end of the Push phase of one arm and the beginning of the Pull phase of the other indicated *Catch-up* coordination ($I_{dc_{adapt}} < 0$%). When one arm began the Pull phase as the other was finishing the Push phase, the coordination was *Opposition* ($I_{dc_{adapt}} = 0$%). When the Pull phase of one arm overlapped with the Push phase of the other, the coordination was *Superposition* ($I_{dc_{adapt}} > 0$%).
2.6. Stroke parameters

The following stroke parameters were calculated from the video recordings at 80%, 85%, 90%, 95%, and 100% of each participant’s SSmax: Stroke length (m) was defined as the distance that the participant’s hip joint marker travelled down the pool with one stroke cycle, calculated as the mean of three stroke cycles; Stroke frequency (Hz) was defined as the number of stroke cycles performed in one second, calculated as the mean of three stroke cycles; Swimming speed (m s⁻¹) was defined as the mean forward speed of the participant over three stroke cycles.

2.7. Statistical analysis

Means and standard deviations were computed for all the measured variables. Normal distribution of the data was verified using the Shapiro-Wilks test. Two separate univariate general linear modeling (GLM) tests were used to compare changes in swimming speed and IdCadapt across the 5% speed increments. A multivariate GLM test was used to compare the changes between IdCaf and IdCun according to the percentage speed increments. Sphericity was adjusted via the Greenhouse-Geisser procedure and verified by means of the Mauchley test. Multiple comparisons were made with the Bonferroni post hoc test. Correlations were calculated among swimming speed, stroke frequency, stroke length, adapted Index of Coordination, and the relative durations of the arm stroke phases, for both the affected- and unaffected-arms, at 100% of SSmax. Pearson Product correlation tests were used in all comparisons except those related to the unaffected-arm’s Entry and Glide and Push phases. As these variables were found to be not normally distributed, Spearman Rank correlation tests were used instead. In all comparisons, the level of significance was set at \( p < .05 \). Statistical analysis procedures were performed using SPSS 14.0 software.

3. Results

Results dealing with swimming speed (SS), the adapted version of the Index of Coordination (IdCadapt), and those of the affected (IdCaf) and unaffected (IdCun) arms are presented in Table 1.

<table>
<thead>
<tr>
<th>Percentage of maximum swimming speed (M ± SD)</th>
<th>( \delta ) (n = 3)</th>
<th>( \bar{\gamma} ) (n = 10)</th>
<th>G.M. (n = 13)</th>
</tr>
</thead>
<tbody>
<tr>
<td>80</td>
<td>85</td>
<td>90</td>
<td>95</td>
</tr>
<tr>
<td>SS (m s⁻¹)</td>
<td>1.23 ± 0.07</td>
<td>1.31 ± 0.08</td>
<td>1.39 ± 0.08</td>
</tr>
<tr>
<td>IdCadapt (%)</td>
<td>−15.3 ± 2.1</td>
<td>−14.6 ± 1.2</td>
<td>−16.0 ± 2.2</td>
</tr>
<tr>
<td>IdCaf (%)</td>
<td>−13.2 ± 7.5</td>
<td>−13.0 ± 8.1</td>
<td>−15.0 ± 7.7</td>
</tr>
<tr>
<td>IdCun (%)</td>
<td>−17.4 ± 6.0</td>
<td>−16.2 ± 7.5</td>
<td>−17.1 ± 8.1</td>
</tr>
<tr>
<td>SS (m s⁻¹)</td>
<td>1.06 ± 0.07</td>
<td>1.11 ± 0.8</td>
<td>1.17 ± 0.9</td>
</tr>
<tr>
<td>IdCadapt (%)</td>
<td>−16.9 ± 5.2</td>
<td>−17.2 ± 6.6</td>
<td>−17.7 ± 6.3</td>
</tr>
<tr>
<td>IdCaf (%)</td>
<td>−27.6 ± 5.3</td>
<td>−27.4 ± 6.1</td>
<td>−26.5 ± 7.0</td>
</tr>
<tr>
<td>IdCun (%)</td>
<td>−6.2 ± 9.4</td>
<td>−7.0 ± 10.4</td>
<td>−8.9 ± 9.4</td>
</tr>
<tr>
<td>SS (m s⁻¹)</td>
<td>1.10 ± 0.10a</td>
<td>1.16 ± 0.12a</td>
<td>1.22 ± 0.12a</td>
</tr>
<tr>
<td>IdCadapt (%)</td>
<td>−16.5 ± 4.5</td>
<td>−16.6 ± 5.9</td>
<td>−17.3 ± 5.6</td>
</tr>
<tr>
<td>IdCaf (%)</td>
<td>−24.0 ± 8.5</td>
<td>−24.1 ± 8.8</td>
<td>−23.8 ± 8.5</td>
</tr>
<tr>
<td>IdCun (%)</td>
<td>−9.0 ± 9.8b</td>
<td>−9.1 ± 10.4b</td>
<td>−10.8 ± 9.5b</td>
</tr>
</tbody>
</table>

\( a \) Significantly different with all SSmax values \( (p < .01) \).
\( b \) Differences between IdCaf and IdCun are statistically significant \( (p < .01) \).
Between 80% and 100% of SSmax there was a significant increase in mean swimming speed (from 1.10 ± 0.10 m s\(^{-1}\) to 1.36 ± 0.14 m s\(^{-1}\); \(p < .05\)). Conversely, across the 5% speed increments, there was no significant difference in mean IdCadapt values. The mean IdCaf values (24.1 ± 8.3%) were significantly lower (\(p < .05\)) than that of the mean IdCun (10.0 ± 9.2%) values at all percentage speed increments. The mean values for both the IdCaf and IdCun were not seen to change as the participants increased their swimming speed, between 80% and 100% of SSmax. At 80% of SSmax, the mean IdCaf value was 24.0 ± 8.5% and the mean IdCun value was 9.0 ± 9.8%. At 100% of SSmax, the mean IdCaf value was 24.3 ± 9.1% and the mean IdCun value was 10.2 ± 8.7%. There was no significant interaction effect on inter-arm coordination.

Inter-swimmer correlation coefficients among swimming speed, stroke frequency, stroke length, adapted Index of Coordination, and relative arm stroke phase durations for both the affected- and unaffected-arms, at maximum swimming speed, are shown in Table 2.

At 100% of SSmax, correlation analysis showed that stroke frequency was significantly related to swimming speed (\(r = .72\); \(p < .05\)), whereas stroke length was not (\(r = .01\)). Both swimming speed (\(r = .59\)) and stroke frequency (\(r = .66\)) were significantly related (\(p < .05\)) to IdCaf. There were moderate but non-significant correlations between swimming speed and IdCun (\(r = -.30\)), and stroke frequency and IdCun (\(r = -.50\)). Stroke frequency was significantly related (\(p < .05\)) to the relative stroke phase durations of the affected-arm (Entry and Glide: \(r = -.74\); Pull: \(r = .71\); Push: \(r = .61\); Recovery: \(r = -.71\)), but not to the stroke phases of the unaffected-arm. IdCaf was also significantly related (\(p < .05\)) to the relative stroke phase durations of the affected-arm (Entry and Glide: \(r = .95\); Pull: \(r = -.31\); Push: \(r = .69\); Recovery: \(r = -.84\)) and to the Push phase of the unaffected-arm (\(r = .69\)).

The fastest swimmers, who had the highest stroke frequencies, exhibited the least amount of catch-up of their affected-arm. Furthermore, the affected-arm of these swimmers spent the shortest percentage time in the Entry and Glide and Recovery phases and the longest percentage time in the Pull and Push phases.

4. Discussion

This study examined the effect of swimming speed on inter-arm coordination and the inter-relationships between swimming speed, inter-arm coordination, and other stroke parameters, in a group of competitive unilateral arm amputee front crawl swimmers.

The mean IdCadapt value of the amputees did not change with an increase in swimming speed up to maximum. At all swimming speeds, arm coordination conformed to that of catch-up. There was
significantly more catch-up (i.e., time delay) of the amputees’ affected-arm ($\text{IdC}_{\text{af}}$) than that of their unaffected-arm ($\text{IdC}_{\text{un}}$), at all swimming speeds. This asymmetrical catch-up did not appear to be affected by an increase in swimming speed, suggesting that swimmers maintained stable inter-arm coordination even though they swam faster. These findings contrast with those found for able-bodied front crawl swimmers. Chollet et al. (2000), Potdevin et al. (2006), and Seifert et al. (2004) all reported that able-bodied swimmers modified their arm coordination with increases in swimming speed. Swimmers switched from using catch-up at slow swimming speeds ($-6.9 \pm 7.1\%$, Chollet et al., 2000; $-11.9 \pm 3.0\%$, Potdevin et al., 2006; $-10.5 \pm 5.3\%$, Seifert et al., 2004), to opposition or superposition at fast swimming speeds ($2.5 \pm 4.4\%$, Chollet et al., 2000; $0.3 \pm 2.0\%$, Potdevin et al., 2006; $2.6 \pm 6.1\%$, Seifert et al., 2004).

The observed differences between the amputee swimmers in this study and those in the Chollet et al. (2000), Potdevin et al. (2006), and Seifert et al. (2004) studies could be accounted for by the way in which arm coordination was quantified and by the difference between the two populations. In the current study the $\text{IdC}_{\text{adapt}}$ was used. It was anticipated that this index would over-estimate the time delay between the beginning of the Pull phase of one arm and the end of the Push phase of the other, in comparison to the original $\text{IdC}$ as defined by Chollet et al. (2000). Even with this difference, changes in arm coordination with increases in swimming speed were still expected. Due to their physical impairment, the amputee swimmers were considerably slower than those in the Chollet et al. (2000), Potdevin et al. (2006), and Seifert et al. (2004) studies. Hence, the amputees would have experienced less resistive force when swimming. As the amputees were unable to attain a speed of $1.8 \text{ m s}^{-1}$, they did not reach the critical point where able-bodied swimmers have been observed to switch their arm coordination to overcome the large resistive forces that occur when swimming around this speed (e.g., Chollet et al., 2000; Seifert et al., 2004; Seifert et al., 2007). This might explain why the rhythmical, intrinsic anti-phase inter-limb relationship of the unilateral arm amputee front crawl swimmers was strongly preserved, despite a change in the task constraint.

The asymmetrical nature of the amputees’ inter-arm coordination has also been observed, to a lesser extent, in able-bodied front crawl swimmers (Seifert, Chollet, & Allard, 2005). In these swimmers, coordination asymmetry has been related to the preferential breathing side and the dominant arm. In the current study, the effect of the breathing action on the swimming stroke was controlled. Therefore, the asymmetrical inter-arm coordination of the amputee swimmers might relate to the different roles that the affected- and unaffected-arm may have within the front crawl arm stroke cycle. It would be expected that the primary function of the unaffected-arm is to generate propulsion. Conversely, the affected-arm might simply function to control inter-arm asymmetry, so that stable repetition of the overall arm stroke cycle is maintained, rather than contribute effectively to propulsion.

Within the current group of swimmers, different amounts of coordination asymmetry were evident between the affected- and unaffected-arm strokes. Four examples of different inter-arm coordination styles are shown in Fig. 3: (1) where the affected- and unaffected-arms showed near-symmetrical catch-up (i.e., both arms had similar $\text{IdC}_{\text{adapt}}$ values, e.g., Swimmer A, who was the fastest male swimmer); (2) where slightly more catch-up was exhibited by the affected-arm (i.e., the $\text{IdC}_{\text{af}}$ was more negative than the $\text{IdC}_{\text{un}}$, e.g., Swimmer B, who was the fastest female swimmer); (3) where there was a large difference between the catch-up of the affected-arm and that of the unaffected-arm (i.e., the $\text{IdC}_{\text{af}}$ was much more negative than the $\text{IdC}_{\text{un}}$, e.g., Swimmer C, who was a mid-level female swimmer); (4) where the unaffected-arm exhibited superposition and the affected-arm exhibited catch-up (e.g., Swimmer D, who was a mid-level female swimmer).

The existence of different inter-arm coordination styles indicated that different compensatory motor strategies had developed within the group of amputee swimmers, as a consequence of their physical impairment. These strategies appeared to be: (1) as one arm was close to exiting the water, the other was close to entering the water (e.g., Swimmers A and B); (2) the affected-arm was held stationary in front of the body as the unaffected-arm was pushed rapidly towards the hip into the Recovery phase, after which time the affected-arm was pulled rapidly under the shoulder (e.g., Swimmer C); (3) as the unaffected-arm recovered, the affected-arm was moved steadily through the underwater phases before being held stationary by the side of the body until such time as the unaffected-arm had commenced its Pull phase (e.g., Swimmer D). However, as propulsion was not quantified in this
study, it is unclear whether some of these motor strategies resulted in more effective stroking technique, than others.

In the current study the nature of the leg-kick in relation to the arm stroke was not examined. In able-bodied front crawl, the leg-kick is thought to be responsible for about 15% of the total propulsion (Deschodt, Arsac, & Rouard, 1999). It is also believed that the leg-kick helps to counteract the rolling action of the trunk (Yanai, 2003) and reduce the resistive forces a swimmer may experience. It would be reasonable to assume that the asymmetrical inter-arm coordination observed in this study would have influenced the nature of the amputees’ leg-kick. This has important implications for how these swimmers reduce resistance effectively when swimming and how they stabilize the rolling action of their trunk. Understanding the inter-relationships between inter-limb coordination and swimming performance would be of great practical importance to swimmers and coaches and warrants further study.

The inter-swimmer correlations in this study showed that there were significant relationships between SS\textsubscript{max} and the stroke frequency and the IdC\textsubscript{af} used at SS\textsubscript{max}. The fastest amputee swimmers used higher stroke frequencies and less catch-up of the affected-arm, when compared to the slower swimmers. Satkunskiene, Schega, Kunze, Birzinyte, and Daly (2005) reported that “more-skilled” swimmers, with various locomotor disabilities, were characterized by greater amounts of superposition and higher stroke frequencies, when compared to “less-skilled” swimmers. Other authors have also shown that stroke frequency significantly correlates with arm coordination ($r = .67$, Chollet et al., 2000; $r = .76$, Seifert et al., 2004). The findings from this study imply that when sprinting, the attainment of a high stroke frequency is mainly influenced by the catch-up style of the affected-arm. Reducing the time delay before initiating the affected-arm pull appears to be a beneficial strategy which allows for attainment of the highest stroke frequencies and swimming speeds.

Fig. 3. Individual examples of four different inter-arm coordination styles exhibited within the group of unilateral arm amputee front crawl swimmers.
At \( SS_{\text{max}} \) there were significant correlations between stroke frequency and the lDCaf and the relative durations of the arm stroke phases of the affected-arm. The fastest amputee’s affected-arm spent less time in the Entry and Glide and Recovery phases and more time in the Pull and Push phases, when compared to the slower swimmers. For able-bodied swimmers (Chollet et al., 2000) and swimmers with a locomotor disability (Satkunskiene et al., 2005) higher lDC values and higher stroke frequencies were significantly related to shorter Entry and Glide phase durations and longer Pull phase durations. In this regard, the faster amputees in this study exhibited similar characteristics to those of other swimmers, when compared to their slower counterparts. This implies that the catch-up style of the affected-arm is mainly influenced by the duration of the Entry and Glide phase of the same arm.

The results from this study show that the inter-arm coordination of the amputees did not change with an increase in swimming speed up to maximum. Swimmers showed significantly more catch-up of their affected-arm compared to their unaffected-arm. When sprinting, the fastest swimmers used higher stroke frequencies and less catch-up of their affected-arm, when compared to the slower swimmers. These findings imply that: (1) unilateral arm amputee front crawl swimmers use an asymmetrical strategy for coordinating their affected-arm relative to their unaffected-arm in order to maintain the stable repetition of their overall arm stroke cycle; and (2) when sprinting, the attainment of a high stroke frequency is influenced mainly by catch-up style of the affected-arm. For these swimmers, reducing the time delay (i.e., the Entry and Glide phase duration) before initiating the affected-arm pull appears to be a beneficial strategy, which allows for the attainment of the highest stroke frequencies and swimming speeds.

Acknowledgments

The authors would like to acknowledge British Disability Swimming for their support in this project, Professor Ross Sanders for the use of his facilities at the Centre for Aquatics Research and Education, The University of Edinburgh, and Miss Casey Lee for her assistance during data collection.

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