STROKE PARAMETERS AND ARM COORDINATION IN COMPETITIVE UNILATERAL ARM AMPUTEE FRONT CRAWL SWIMMERS

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The aims of this study were to: (1) determine the changes in stroke parameters and arm coordination as a function of swimming speed; and (2) examine the relationships between stroke parameters and arm coordination, for competitive unilateral arm amputee front crawl swimmers. Thirteen highly-trained swimmers (3 male, 10 female) were filmed underwater from lateral views during six increasingly faster 25 m front crawl trials. Increases in swimming speed were achieved by an increase in stroke frequency which coincided with a decrease in stroke length. All swimmers showed asymmetric coordination between their affected and unaffected arm pulls, which was not affected by an increase in swimming speed up to maximum. The fastest amputee swimmers used higher stroke frequencies and less catch-up coordination before their affected arm pull, when compared to the slower swimmers. Reducing the time delay before initiating the affected arm pull appears to be beneficial for successful swimming performance.

KEY WORDS: aquatics, biomechanics, motor control, disability sport.

INTRODUCTION: Swimming speed (SS) is the product of stroke frequency (SF) and stroke length (SL). Stroke frequency is determined by the rate at which a swimmer's limb segments move, while stroke length is determined by the propulsion generated by a swimmer and the resistance experienced. Success in competitive swimming depends on a swimmer's ability to maximise propulsion and minimise resistance. The timing of propulsion relative to resistance becomes crucial when considering the effectiveness of a swimmer's stroking technique.

The Index of Coordination (IdC) is often used to quantify the coordination of arm movements during front crawl swimming. The IdC measures the time lag (expressed at a percentage of total stroke time) between the beginning of propulsion in one arm stroke and the end of propulsion in the other. As described by Chollet et al. (2000), arm coordination conforms to one of three major models: (1) The model of catch-up describes a time delay between the propulsive phases of the two arms (i.e. IdC < 0%); (2) The model of 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) The superposition model, describes an overlap, to a greater or lesser extent, in the propulsive phases (i.e. IdC > 0%).
Able-bodied swimmers have been shown to modify their arm coordination with increases in swimming speed (Chollet et al., 2000; Potdevin et al., 2006). Swimmers switched from using catch-up at slow swimming speeds, to opposition or superposition at fast swimming speeds. This change coincided with an increase in stroke frequency and a decrease in stroke length. For swimmers with various loco-motor disabilities, Satkunskiene et al. (2005) reported that "more-skilled" swimmers were characterised by greater amounts of superposition and higher stroke frequencies, when compared to "less-skilled" swimmers.
No such examination of arm coordination has been undertaken with a single homogenous group of highly-trained swimmers with the same physical impairment. Faster unilateral arm amputee front crawl swimmers are able to attain higher stroke frequencies, when compared to their slower counterparts (Osborough et al., 2009). However, large variations in the timing of the underwater arm stroke movements have been observed within this group of swimmers. It is unclear what influence these variations in inter-arm coordination might have on performance. The aims of this study were to: (1) determine the changes in stroke parameters and arm coordination as a function of swimming speed; and (2) examine the

relationships between stroke parameters and arm coordination, for competitive unilateral arm amputee front crawl swimmers.

METHODS: Data Collection: Thirteen (3 male and 10 female) competitive swimmers (age 16.9 ± 3.1 yrs) consented to participate in this study. All the participants were single-arm amputees, at the level of the elbow. The mean 50 m front crawl personal best time was 32.7 ± 3.1 s. Twelve of the swimmers competed in the International Paralympic Committee S9 classification for front crawl; one male swimmer competed in the S8 classification. 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.

After being randomly allocated into one of two test groups, participants completed six 25 m front crawl trials, counterbalanced from slow to maximum swimming speed (SS_{max}). 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 pool. Two digital video camcorders (Panasonic NVDS33), sampling at 50 Hz with a shutter speed of 1/350 s were used to film the participants. 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. This set-up enabled the participants to be filmed under the water, from opposite sides, over the 10 m test section.

Data Analysis: The digital video footage was transferred to a laptop computer and analysed using SIMI Motion 7.2 software. Three consecutive, non-breathing stroke cycles for each participant, were then selected for analysis. The estimated locations of the gleno-humeral joint centre and the elbow joint centre of both the affected and unaffected arms were digitised at 50 Hz to obtain the angular position of the limbs, as a function of time.
The following variables were then determined from the digitised data or video recordings at 80%, 85%, 90%, 95% and 100% of each participant's SS_{max}: IdC_{aff} (%) - lag time between the beginning of the pull phase with the affected arm and the end of the push phase with the unaffected arm; IdC_{un} (%) - lag time between the beginning of the pull phase of the unaffected arm and the end of the push phase with the affected arm; IdC_{adapt} (%) - mean of IdC_{aff} and IdC_{un}; SL (m) - distance travelled down the pool with one stroke cycle; SF (Hz) - number of stroke cycles performed in one second; SS ($m{\cdot}s^{-1}$) - mean forward speed of the participant over three stroke cycles.
Repeated measures general linear modelling tests were used to compare the changes in the dependent variables between the percentage swimming speeds. Correlations were calculated among the dependent variables at 100% of SS_{max}. In all comparisons, the level of statistical significance was set at $p < 0.05$.

RESULTS:

Table 1: Mean ± S.D. stroke parameters at 80%, 85%, 90%, 95% and 100% of SS_{max}.

	Percentage of maximum swimming speed (*M* ± *SD*)				
	80	85	90	95	100
SS ($m{\cdot}s^{-1}$)	1.10 ± 0.10 [a]	1.16 ± 0.12 [a]	1.22 ± 0.12 [a]	1.29 ± 0.13 [a]	1.36 ± 0.14 [a]
SL (m)	1.78 ± 0.15 [b]	1.77 ± 0.14 [b]	1.73 ± 0.14	1.71 ± 0.15 [c]	1.66 ± 0.16
SF (Hz)	0.57 ± 0.18	0.66 ± 0.08 [d]	0.71 ± 0.08	0.76 ± 0.09 [a]	0.82 ± 0.11 [a]

[a] Significantly different with all percentage SS_{max} values ($p < 0.01$). [b] Significantly different with 100% of SS_{max} value ($p < 0.05$). [c] Significantly different with 85% of SS_{max} value ($p < 0.05$). [d] Significantly different with 90% of SS_{max} value ($p < 0.01$).

The mean and standard deviations for the stroke parameters are presented in Table 1. Between the first swim at 80% of SS_{max} and the last swim at 100% of SS_{max}, mean stroke frequency significantly increased (from 0.57 ± 0.18 Hz to 0.82 ± 0.11 Hz; $p < 0.01$) and mean stroke length significantly decreased (from 1.78 ± 0.15 m to 1.66 ± 0.16 m; $p < 0.05$) in conjunction with a significant increase in mean swimming speed (from 1.10 ± 1.10 $m{\cdot}s^{-1}$ to 1.36 ± 0.14 $m{\cdot}s^{-1}$; $p < 0.01$).

Table 2: Mean ± S.D. arm coordination variables at 80%, 85%, 90%, 95% and 100% of SS_{max}.

	Percentage of maximum swimming speed ($M \pm SD$)				
	80	85	90	95	100
IdC_{adpt} (%)	-16.5 ± 4.5	-16.6 ± 5.9	-17.3 ± 5.6	-17.5 ± 5.3	-17.3 ± 5.2
IdC_{aff} (%)	-24.0 ± 8.5	-24.1 ± 8.8	-23.8 ± 8.5	-24.1 ± 7.7	-24.3 ± 9.1
IdC_{un} (%)	-9.0 ± 9.8 [a]	-9.1 ± 10.4 [a]	-10.8 ± 9.5 [a]	-10.8 ± 8.8 [a]	-10.2 ± 8.7 [a]

[a] Differences between IdC_{aff} and IdC_{un} are statistically significant ($p < 0.01$).

Results dealing with the arm coordination variables are reported in Table 2. There were no significant differences in mean IdC_{adapt} values across the five percentage speed increments. The mean IdC_{aff} values (- 24.1 ± 8.3 %) were significantly lower ($p < 0.01$) than that of the mean IdC_{un} values (- 10.0 ± 9.2 %) at all percentage swimming speeds. The values for both the IdC_{aff} and IdC_{un} were not seen to change as the participants increased their swimming speed (- 24.0 ± 8.5 % vs. - 24.3 ± 9.1 % and - 9.0 ± 9.8 % vs. -10.2 ± 8.7 % for IdC_{aff} and IdC_{un} respectively). There was no significant interaction effect on inter-arm coordination.

Table 3: Inter-correlations among stroke parameters and arm coordination variables at SS_{max}.

	Swimming speed ($m \cdot s^{-1}$)	Stroke frequency (Hz)	IdC_{aff} (%)
Stroke frequency (Hz)	0.72 [b]		
Stroke length (m)	0.01	- 0.68 [a]	
IdC_{adpt} (%)	0.26	0.54	
IdC_{aff} (%)	0.59 [a]	0.66 [a]	
IdC_{un} (%)	- 0.30	- 0.50	- 0.31

[a] Correlations are statistically significant ($p < 0.05$). [b] Correlations are statistically significant ($p < 0.01$).

Inter-correlation coefficients among stroke parameters and arm coordination variables at 100% of SS_{max} are shown in Table 3. At 100% of SS_{max}, stroke frequency was significantly related to swimming speed ($r = 0.72$; $p < 0.01$) whereas stroke length was not ($r = 0.01$). Both swimming speed ($r = 0.59$) and stroke frequency ($r = 0.66$) were significantly related ($p < 0.05$) to IdC_{aff}. There were moderate but non-significant correlations between swimming speed and IdC_{un} ($r = - 0.30$), and stroke frequency and IdC_{un} ($r = - 0.50$).

DISCUSSION: The aims of this study were to: (1) determine the changes in stroke parameters and arm coordination as a function of swimming speed; and (2) examine the relationships between stroke parameters and arm coordination, for competitive unilateral arm amputee front crawl swimmers.

The arm amputee swimmers in this study achieved progressive increases in swimming speed by increasing stroke frequency. The increase in stroke frequency coincided with a decrease in stroke length, this being similar for able-bodied swimmers (Chollet et al., 2000; Potdevin et al., 2006). In comparison, the mean SS_{max} of the amputees was substantially slower than that of able-bodied swimmers (1.81 ± 0.1 $m \cdot s^{-1}$ for 14 high-performing male and females, Chollet et al., 2000; 1.63 ± 0.12 $m \cdot s^{-1}$ for 13 expert males, Potdevin et al., 2006). The amputees had lower stroke frequencies when compared to these able-bodied swimmers (0.90 ± 0.1 Hz, Chollet et al., 2000; 0.92 Hz, Potdevin et al., 2006). The amputees had appreciably shorter stroke lengths, when again compared to these able-bodied swimmers (2.01 ± 0.1 m, Chollet et al., 2000; 1.83 ± 0.14 m Potdevin et al., 2006). These differences can be attributed to the physical impairment of the amputees but might also be influenced by the predominate gender and the relatively small stature of the amputee swimmers.

The IdC_{adapt}, IdC_{aff} and IdC_{un} values of the amputees did not change with an increase in swimming speed. At all swimming speeds arm coordination conformed to the front crawl catch-up model (i.e. IdC < 0%). There was significantly more catch-up before the amputees' affected arm pull than before their unaffected arm pull, at all swimming speeds. Furthermore, 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. This finding contrasts with that of able-bodied front crawl swimmers. Both Chollet et al. (2000) and Potdevin et al. (2006) reported that able-bodied swimmers switched from using catch-up at slow swimming speeds, to opposition or superposition at fast swimming speeds. Being deprived of an important propelling limb and the inability to attain the higher swimming speeds of those tested by Chollet et al. (2000) and Potdevin et al. (2006) might account for the observed differences in the arm coordination values between the amputee and able-bodied front crawl swimmers.
There were significant inter-swimmer correlations between SS_{max} and the stroke frequency and the IdC_{aff} used at SS_{max}. This indicates that the fastest amputee swimmers used higher stroke frequencies and less catch-up before their affected arm pull, when compared to the slower swimmers. This finding has similarities to those reported for able-bodied swimmers and swimmers with loco-motor disabilities. Satkunskiene et al. (2005) reported that "more-skilled" swimmers were characterised by greater amounts of superposition and higher stroke frequencies, when compared to "less-skilled" swimmers. Chollet et al. (2000) showed that for able-bodied swimmers, stroke frequency was significantly correlated (r = 0.67) with arm coordination. For the fastest unilateral arm amputee front crawl swimmers in this study, reducing the time delay before initiating the affected arm pull appears to be a motor control strategy for the attainment of the highest stroke frequencies and swimming speeds.

CONCLUSION: In the current study the findings imply that to improve their maximum swimming speed, unilateral arm amputees should focus on increasing their stroke frequency, rather than swimming with the longest possible stroke length. All swimmers showed asymmetric coordination between their affected and unaffected arm pulls. This asymmetry did not appear to be affected by an increase in swimming speed up to maximum. The quickest swimmers exhibited less front crawl catch-up coordination before their affected arm pull and higher stroke frequencies, when compared to their slower counterparts. For successful swimming performance, reducing the time delay before initiating the affected arm pull appears to be beneficial for competitive front crawl swimmers with a single-arm amputation.

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