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Research article

Variability of coordination parameters at 400-m front crawl swimming pace

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Abstract
This study examined the variability of physiological, perceptual, stroke and coordination parameters in both genders during several swim trials at the 400-m pace speed. Twelve national level competitors (6 men, 6 women) swam 400-m at maximal speed. They then swam three additional trials (100, 200 and 300-m) at the pace (speed) of the previous 400-m. Three cameras were used to determine stroke cycle [speed (V), stroke length (SL), stroke rate (SR)] and coordination [index of coordination (IdC), stroke phases] parameters. Physiological [heart rate (HR) and lactate [La-] and perceptual [subjective workload (TWL)] parameters were assessed after each swim trial. Inter-trial data indicated that HR, [La-] and TWL increased significantly with the distance swum ($p < 0.05$). Inter-trial comparison did not show significant variation of stroke cycle and coordination parameters. Inter-lap data were examined within the 400-m and showed that V and SL decreased significantly at the beginning of the trial ($p < 0.05$), but IdC and SR remained unchanged ($p > 0.05$). Thus, despite changes in both physiological and perceptual responses consecutive to increasing fatigue, coordination parameters remained stable during an all-out 400-m freestyle swim. The examination of these parameters based on short-distance trials appears then to be valid, which offers interesting perspectives for swim testing.

Key words: Testing, motor control, biomechanics, variability, fatigue, competitive swimming.

Introduction

Swimming speed (V, in $m.s^{-1}$) is the product of stroke rate (SR, in Hz) and stroke length (SL, in m), expressed as V = (SR×SL) (Craig et al., 1979). Long stroke lengths are assumed to characterise high expertise (Chollet et al., 1997; Wakayoshi et al., 1993). However, other parameters have also been associated with expertise, such as inter-arm coordination. Although Nikodelis et al. (2005), did not find any relationship between performance level and inter-arm coordination, different studies using the Index of Coordination (IdC) (Chollet et al., 2000), showed this parameter to be an important feature in performance. The IdC measures the mean lag time that separates the propulsive phases from one arm to the other. For a given swim pace, the best swimmers are able to maximise the time devoted to propulsion within the cycle, and exhibit thus higher IdC (Chollet et al., 2000) as compared with less experienced swimmers. Moreover, the IdC changes with speed (or pace). At slow paces, expert swimmers have a long gliding phase (IdC<0%), while at fast paces, they overlap the propulsive phases (IdC>0%); in comparison, the inter-arm coordination of non-expert swimmers remains in catch-up mode (IdC<0%) (Seifert et al., 2004). Thus, expert swimmers are able to increase this time devoted for propulsion (and IdC) efficiently, since at the same time their stroke length remains great as compared with that of less experienced swimmers (Seifert et al., 2007). However, independently from performance level, IdC has been shown to be sensitive to anthropometric characteristics, since women exhibit generally lower IdCs as compared with men (Seifert et al., 2004).

During a constant all-out swim, experts are also characterised by greater stability in their coordination pattern than other swimmers. Alberty et al. (2005) and Seifert et al. (2007) showed that speed and SL decreased, whereas IdC increased from the beginning to end of 100-m and 200-m freestyle trials swum at maximal speed. These changes were attributed to fatigue. However, Toussaint et al. (2006) and Chollet et al. (1997) showed that the best swimmers in 100-m trials were characterised by smaller decreases in both V and SL. The best swimmers also showed greater stability in their coordination parameters (IdC and stroke phases) (Seifert et al., 2007), but this stability has never been demonstrated for distances longer than 200-m, although Craig et al. (1985) outlined slightly different patterns of race management for middle-distance swimming. It would thus be interesting to examine the stability of stroke cycle and coordination parameters for distances that mostly involve the aerobic pathways. Nomura et al. (1998) showed than this is the case for swim distances longer than 400-m. More precisely, Laffite et al. (2004) estimated the contribution of the aerobic system to be 81.1 ± 3.9% of total energy output, where total energy output is computed based on the aerobic and anaerobic lactic energy resources, since the alactic ones are negligible (Barbosa et al., 2006).

In general, skilled task performances are characterised by low variability in the pattern (Bartlett et al., 2000; Davids et al., 2006). According to Bates et al. (2004), variability refers to the variations of the same response for a specific set of conditions. In swimming, Alberty et al., (2006) showed that maximal tests of constant time, constant distance and constant speed were all reproducible. However, these authors investigated only speed and time parameters. In fact, little is known about the variability of coordination parameters in swimming. Yet this issue is important, since these parameters are often measured in swim testing during simulated race paces on short distances (Chollet et al., 2000; Schnitzler et al., 2008; Seifert et al., 2004). The assumption of stable stroke cycle and coordination parameters should thus be verified to ensure

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the validity of the measures.

The aim of this study was to examine the variability of physiological, perceptual, stroke cycle and coordination parameters in swimming. We hypothesised that stroke cycle and coordination parameters in expert swimmers would not vary significantly between trials of various lengths swum at the 400-m pace or between laps within a 400-m swam at maximal speed despite increase of fatigue with distance.

Methods

Subjects

Twelve expert swimmers (6 men, 6 women) competing at the French national level volunteered for this study. Their mean ± SD age, percentage of short-course world record velocity on 400-m, experiment time on 400-m (s), percentage of personal record achieved during the experiment, body mass (kg), height (m), arm span (cm) were: 18.2 ± 2.2 years, 82.2 ± 2.9%, 288 ± 11.1 s, 88.2 ± 3.9%, 66.2 ± 9.9 kg, 1.77 ± 1.1 m, 184.3 ± 16.8 cm for the men and 18.7 ± 3.8 years, 82.1 ± 2.9%, 308 ± 12 s, 88.1 ± 3.9%, 54.5 ± 8.8 kg, 1.67 ± 0.04 m and 164.8 ± 8.2 cm for the women.

The percentage of the world record (competition) was taken as an indicator of expertise. For this study, it was calculated on the basis of each subject's best competitive time in the 400-m event of the current season, compared with the time of the current world record in the short-course event (2007), and expressed as a percentage (%WR). The experiment took place during a training session. The protocol was fully explained to the swimmers and they provided written consent to participate in the study, which was approved by the university ethics committee.

Swim trials

For all trials, the swimmers had a standardised warm-up under the supervision of their coach. There was no further training planned before or after this experiment. In a 25-m pool, the swimmers performed a 400-m freestyle swim at maximal speed. The next day, they performed 100-m and 200-m trials with a 20-minute of active recovery between trials. The subjects were instructed to perform light leg and front crawl exercises, which were monitored by the coach. To ensure the subjects had enough rest, we measured the lactate before the 200-m trial. The subjects were authorised to swim if they were within the range of rest values, i.e. between 1 and 2.1 $mmol.l^{-1}$. This appeared to be likely in each case. On the following day, they swam 300-m at the same speed. For all trials, departure was made in the water (no diving). To calculate the speed at which the 100-, 200- and 300-m trials had to be swum, the mean speed from the 400-m was calculated. For the 100-, 200- and 300-m trials, a researcher gave the swimmers a sound signal every 50-m to ensure that their speed conformed to the mean speed of the previous 400-m. The researcher did this by referring to a timetable drawn up for each swimmer, indicating the time pace for each 50-m. The swimmers then had to coordinate their turns with the signal. We decided to stop the swimmers if more than 2 seconds elapsed between the signal and the turn. This occurred on two occasions, and the swimmers then had to return the next day to complete the trial again.

Video analysis

The swim trials were videotaped by three mini-dv video cameras (50 Hz, Sony DCRTRV6E, Tokyo, Japan). Two cameras were placed underwater in a specially designed box (Sony SPK-DVF3, Tokyo, Japan). The first camera, which videotaped in the sagittal plane, was fixed in the middle of the pool. An operator placed behind this underwater camera followed the swimmer, tracking the entire trial. The other underwater camera was in a fixed transverse plan, 20 cm below the surface of the water. A third fixed camera videotaped the trials of each swimmer with a profile view from above the water. Three swim stroke cycles were analysed every 50-m. As the camera placed underwater in side view did not move parallel to the swimmer, we took into consideration the swim stroke cycle during which the swimmer was perpendicular to the camera, the swim stroke cycle before it and the swim stroke cycle after it to correct the parallax effect. This methodology has been shown to be reliable by Chollet et al. (2000), since the calculation of spatio-temporal and coordination parameters are made on the basis of the mean value of these three stroke cycles.

The three cameras were synchronised with Dartfish software (Dartfish© ProSuite 4.0, 2005, Switzerland), the keypoint for synchronization being the entry of the hand into the water.

Physiological values

During and after all trials, heart rate (HR) was measured with a Polar S810 (Polar, Kempele, Finland), and the sensor was fixed to the chest with a special tape used in medicine (Elastoplaste HB, 2.5m×6cm). The HR sample data was set as 5-s. The capillary lactate concentration [La-] was measured at the fingertip 1, 3 and 5 minutes after every trial with a LactatePro meter (Accusport, Arkray, Tokyo). For these two parameters, peak values were taken into account.

Subjective workload assessment

Immediately upon leaving the pool after a trial, the swimmers sat in a chair to complete the NASA-TLX, a subjective assessment of workload questionnaire (Hart and Staveland, 1982), in its French version (Rubio et al., 2004). It contains six subscales that define the different dimensions of a task: (i) mental demand, (ii) physical demand, (iii) own performance, (iv) temporal demand, (v) effort, and (vi) frustration. We used non-weighted methods, and the total workload (TWL) was the average of the six subscales, as previously done by Schnitzler et al. (2007).

Stroking parameters

Video analysis allowed the calculation of mean speed every 50-m (V50). The time taken to cover this distance was measured from the first image when the feet left the wall. The end of the swim trial was taken to be the moment when the swimmer's hand touched the wall. All measurements were made with a precision of 0.02 seconds. The stroke rate (SR) was calculated from three complete cycles taken in the middle of the pool for every 50-m segment and expressed in Hz. The stroke length (SL) was calculated from the V50 and SR values (SL = V x SR).

Arm stroke phases and coordination

The arm stroke was divided into four distinct stroke phases, similar to those presented in the front crawl study by Chollet et al. (2000):

Phase A: Entry and catch of the hand in the water, which corresponds to the time between the entry of the hand into the water and the beginning of its backward movement.

Phase B: Pull phase, which corresponds to the time between the beginning of the backward movement of the hand and its entry into the plane vertical to the shoulder.

Phase C: Push phase, which corresponds to the time between the positioning of the hand below the shoulder and its exit from the water. The pull and the push phases correspond to the arm propulsive time.

Phase D: Recovery phase, which was considered to correspond to the time between the exit of the hand from the water and its following entry into the water.

The absolute duration of these stroke phases was measured for each arm over three complete stroke cycles. The duration of each phase was measured every 50-m of all trials with a precision of 0.02 s and was expressed as a percentage of the duration of a complete arm stroke cycle. The summation of the pull and push phase durations was considered to be correspondent to the arm propulsive time (Ppr). The mean duration of a complete stroke cycle was the sum of the propulsive and non-propulsive phases.

The Index of Coordination (IdC) calculated the time gap between the propulsion of the two arms as a percentage of the duration of the complete arm stroke cycle (Chollet et al., 2000). IdC was the mean of IdC_{left} and IdC_{right}:

$$IdC_{left} = [(Time_{\text{End of phase C for left arm}} - Time_{\text{Beginning of phase B for right arm}}) \times 100] / Duration_{\text{Complete cycle}}$$

$$IdC_{right} = [(Time_{\text{End of phase C right arm}} - Time_{\text{Beginning of phase B for left arm}}) \times 100] / Duration_{\text{Complete cycle}}$$

Every 50-m, a mean IdC was calculated on three complete stroke cycles. So the IdC was available 8, 6, 4, and 2 times for the 400-m, 300-m, 200-m, and 100-m swim trials, respectively. The IdC was expressed as a percentage of the mean stroke cycle duration. When there was a lag time between the propulsive phases of the two arms, the stroke cycle coordination was called “catch-up” (IdC<0). When the propulsive phase of one arm started at the time the other arm finished 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).

Statistical analysis

Exploratory analysis: Statistical analyses were made with Minitab 14 software (Minitab Inc., State College, PA, USA, 2003). Normality of distribution (Ryan-Joiner test, similar to Shapiro-Wilk) and homogeneity of variance between populations (Bartlett test) were checked for all parameters and allowed parametric statistics.

Inter-trial comparison: A three-way ANOVA [(*fixed factors*: swim trial (4 levels: 100-m, 200-m, 300 m, 400-m), gender (2 levels); *random factor*: subject (12 levels)] analysed the changes in physiological (HR, [La-]), perceptual (TWL), stroke cycle (V50, SL, SR) and coordination (IdC, A, B, C, D, Ppr) parameters between the 100-m, 200-m, 300-m and 400-m swim trials. Tukey post-hoc tests examined the differences. The number of values taken into account was thus n = 12 swimmers × 4 trials = 48. An overall coefficient of variation (CV) was calculated as the mean ± SD of the individual’s CV over the four trials. A one-way ANOVA was then used to compare the inter-trial mean CV values.

A test-retest correlation matrix was set between all distance trials for the stroke cycle and coordination parameters. A one-way ANOVA was used to compare these coefficients of correlation across stroke cycle and coordination parameters.

Inter-lap comparison

A three-way ANOVA [(*fixed factors*: swim distance (8 levels: 50-m, 100-m, 150-m, 200-m, 250-m, 300-m, 350-m, 400-m); gender (2 levels); *random factor*: subject (12 levels)] examined inter-lap differences in stroke cycle (V50, SL, SR,) and coordination (IdC, A, B, C, D, Ppr) parameters in the maximal 400-m trial. The number of values taken into account was thus n = 12 swimmers ×8 laps = 96. Tukey post-hoc tests examined the differences.

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

Results

Inter-trial variability of physiological, perceptual, stroke cycle and coordination parameters at the 400-m pace

Table 1 presents the changes in the physiological and perceptual parameters from the 100-m to the 400-m trials.

Table 1. Inter-trial values of physiological and perceptual parameters. Data are means (±SD).

		HR	La	TWL
	100	165 (12)	3.6 (.6)	4.0 (1.9)
Men	200	174 (9)	6.6 (1.0)	4.5 (1.7)
	300	180 (9)	7.5 (1.4)	5.0 (1.9)
	400	188 (5)	10.5 (2.0)	6.3 (1.1)
Trial distance effect		*	*	*
	100	167 (6)	4.1 (1.0)	2.8 (1.4)
Women	200	176 (7)	5.9 (1.7)	4.1 (1.5)
	300	180 (4)	6.2 (2.0)	5.0 (1.6)
	400	186 (5)	8.3 (2.5)	5.0 (.5)
Trial distance effect		*	*	*

* Significant trial effect with $p < 0.05$. HR: heart rate (bpm); La: peak post-exercise lactate value ($mmol.l^{-1}$); TWL: total workload.

The heart rate (HR), lactate [La-] and total workload (TWL) increased significantly with distance for both genders ($p < 0.05$). Tukey post-hoc tests showed that for both genders: (i) HR increased significantly from 100 to 400-m, although between 200 and 300-m the values were

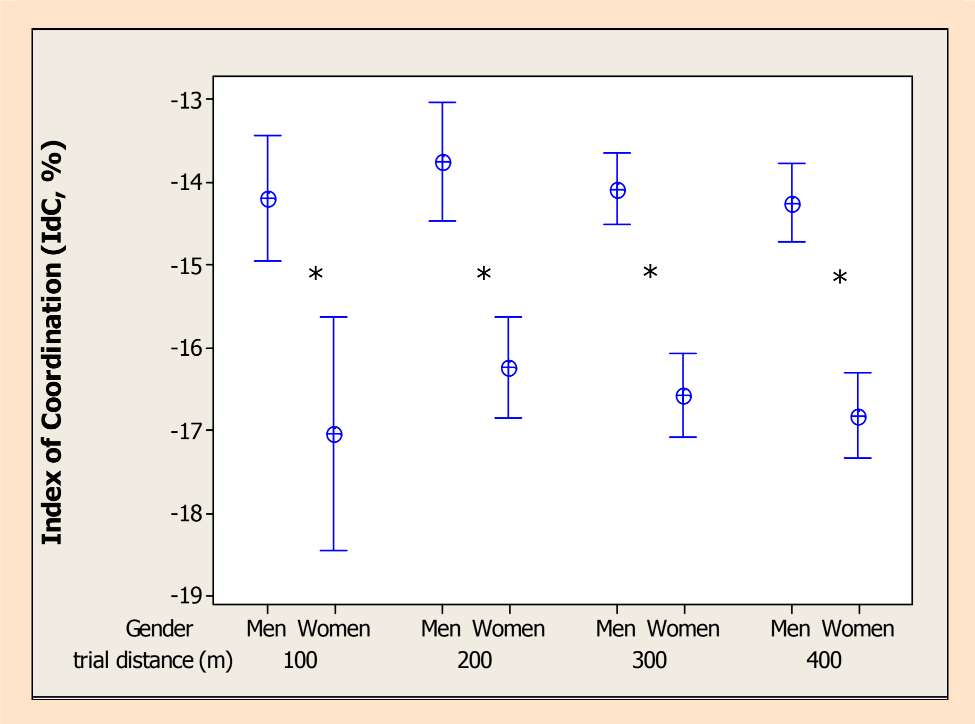

Figure 1. Inter- trial Index of Coordination for both genders. * significant difference between Men and Women for each distance trial ($p < 0.05$).

not statistically different; (ii) lactate values, except between 200-m and 300-m, increased significantly from 100 to 400-m; and (iii) TWL differed significantly between 100- and 300-m and 100 and 400-m.

Men presented significantly higher V, SL, IdC, B and Ppr phases, whereas the duration of phase A (catch) was significantly higher in women ($p < 0.05$). No significant differences were found for any other stroke cycle parameter (V, SR, SL) or coordination parameter (IdC, A, B, C, D, Ppr) between trials. Figure 1 illustrates the mean IdCs values for all trials.

The CVs for the swim trials are presented in Table 2. No significant differences in the distance effect were detected for either stroke cycle or coordination parameters.

The results for the retest coefficients of correlation are presented in Table 3. The retest correlation was significant for all parameters. No significant difference in coefficients of correlation was detected in the stroke cycle or coordination parameters.

Inter-lap variability of the all-out 400-m swim bout

The changes in stroking and coordination parameters for the maximal 400-m swim trial are presented in Table 4.

ANOVAs showed distance effects on V and SL for the stroke cycle parameters, and A and D for the coordination parameters ($p < 0.05$). As outlined in Figure 2, the Tukey post-hoc situated the difference between the initial 50-m and the rest of the trial for V (Figure 2a), A and D ($p < 0.05$), and between the initial 50-m and 350-m and 400-m for SL (Figure 2c). No significant difference was observed throughout the maximal 400-m trial for SR or IdC (Figure 2b, d), or for B, C and Ppr.

No gender×distance interaction was found for any kinematical or coordination parameter.

Table 3. Inter-trial coefficient of correlation of test-retest procedure for stroke and coordination parameters. Data are means (±SD).

V	SR	SL	IdC	A	B	C	D	PPr	Mean
.89	.90	.90	.84	.91	.84	.82	.89	.82	.87
(.04)	(.04)	(.04)	(.07)	(.04)	(.09)	(.05)	(.05)	(.08)	(.07)

Discussion

The objective of the study was to examine the inter-trial and inter-lap variability of swim trials at the 400-m pace in experienced swimmers. The main result shows that the coordination parameters remained stable across swim trials despite the increase in fatigue during maximal effort.

Table 2. Inter-trial coefficient of variation for distance trial for stroke and coordination parameters. Data are means (±SD).

	CV V	CV SR	CV SL	CV IdC	CV A	CV B	CV C	CV D	CV Ppr
100	2.8 (1.9)	3.5 (1.8)	3.6 (2.3)	10.2 (4.5)	3.1 (2.3)	10.1 (8.2)	4.2 (2.3)	4.5 (2.6)	4.1 (2.6)
200	3.2 (1.9)	3.8 (1.4)	4.7 (1.9)	10.6 (3.1)	4.1 (1.7)	9.1 (3.4)	5.8 (2.6)	6.2 (2.7)	4.4 (1.0)
300	2.8 (1.2)	2.9 (1.3)	3.8 (1.5)	8.6 (4.4)	3.5 (1.0)	6.2 (2.2)	6.7 (2.3)	6.1 (2.0)	4.0 (1.8)
400	4.2 (1.6)	3.8 (1.7)	4.1 (1.3)	7.9 (2.7)	3.7 (1.6)	7.1 (2.4)	4.4 (1.7)	6.0 (2.0)	3.5 (1.4)

CV V: coefficient of variation of velocity; CV SR: coefficient of variation on stroke rate; CV SL: coefficient of variation on stroke length; CV IdC: coefficient of variation on index of coordination; CV A, B, C, D, Ppr: Coefficient of variation on catch (A), pull (B), push (C), recovery (D), arm propulsive time (Ppr).

Table 4. Inter-lap distance effect on stroking and coordination parameters.

		V ($m \cdot s^{-1}$)	SR (Hz)	SL (m)	IdC (%)	A (%)	B (%)	C (%)	D (%)	Ppr (%)
	50	1.35 (.08)	.63 (.06)	2.16 (.25)	15.4 (2.9)	41.8 (3.6)	14.7 (2.4)	19.7 (1.2)	23.9 (2.6)	34.4 (2.9)
	100	1.25 (.07)	.59 (.06)	2.12 (.24)	15.9 (2.3)	44.1 (3.3)	14.3 (2.2)	19.9 (1.5)	21.7 (2.5)	34.2 (2.1)
	150	1.25 (.07)	.60 (.06)	2.12 (.26)	15.9 (2.3)	43.7 (4.0)	14.4 (3.0)	19.8 (1.6)	22.2 (2.5)	34.2 (2.4)
Distance	200	1.24 (.06)	.59 (.05)	2.11 (.22)	15.7 (2.3)	44.2 (3.2)	14.1 (2.6)	20.0 (1.8)	21.7 (2.3)	34.1 (2.2)
	250	1.25 (.06)	.60 (.05)	2.12 (.21)	15.4 (1.5)	43.8 (3.5)	14.6 (2.6)	20.1 (2.0)	21.5 (2.7)	34.7 (1,6)
	300	1.24 (.07)	.60 (.05)	2.08 (.24)	15.5 (2.4)	44.3 (3.4)	14.0 (2.4)	20.3 (1.7)	21.4 (2.3)	34.3 (2.3)
	350	1.25 (.06)	.61 (.04)	2.07 (.18)	15.0 (2.4)	43.6 (3.7)	14.9 (2.9)	20.2 (2.0)	21.3 (2.5)	35.1 (2.4)
	400	1.25 (.09)	.62 (.05)	2.04 (.19)	15.6 (2.6)	44.0 (4.0)	14.5 (2.9)	20.0 (1.7)	21.5 (2.4)	34.4 (2.7)
		*	NS	*	NS	*	NS	NS	*	NS
Gender	Women	1.22 (.01)	.60 (.01)	2.05 (.03)	16.8 (.3)	44.8 (.5)	13.0 (.4)	20.2 (.2)	22.1 (.4)	332 (.3)
	Men	1.29 (.01)	.60 (.01)	2.15 (.03)	14.2 (.3)	42.6 (.4)	15.9 (.2)	19.8 (.2)	21.7 (.3)	35.7 (.3)
		δ	NS	δ	δ	δ	δ	NS	NS	δ

* trial distance effect with $p < 0.05$. δ : gender effect with $p < 0.05$. NS: non-significant change. V: velocity; SR: stroke rate; SL: Stroke length; IdC: Index of coordination; A: catch phase; B: pull phase; C: push phase; D: recovery phase; Ppr: arm propulsive time.

The swimming speed for the 400-m trial was quite slow compared with competition time, since it represented only 88.7% of competition speed. However, swimmers were tested during a training session. Each subject swam the trial alone, without the pressure of opponents, and started in the water; these factors might have modified performance and race management. Moreover, the swimmers were not in peak shape, since the experiment took place 4 to 6 weeks before the major competition (by which time they all reached their best performance level). Last, circadian rhythm might have played a role in the overall performance. Indeed, the experiment took place in the early morning, at a time (between 6 and 8 am) when athletic performance is hampered by low body temperature and arousal level (Atkinson et al., 1996). In this particular testing context, the swimmers thus seemed to accentuate the gliding phase and this was confirmed by the IdC values, which were lower than those usually found in the literature for this race pace (Chollet et al., 2000). By promoting the non-propulsive phase, thus glide, this race management strategy is thought to lower the metabolic cost of effort. Inter-limb synchronisation influences stroke cycle parameters, thereby influencing swimming speed, which is consequently reduced. However, the swimmers still showed a high commitment to the study, as evidenced by their HR (187±4.9 bpm), [La-] (9.9 ± 1.73 $mmol.l^{-1}$) and TWL (6.3 ± 1.1) values after the maximal 400-m trial. These values are comparable to those found in similar testing protocols (Laffite et al., 2004; Schnitzler et al., 2007; Wakayoshi et al., 1993).

Inter-trial variability

Costill (1992) noted that the combination of physiological and perceptual parameters reliably indicates the stress imposed on swimmers. For this study, we analysed the changes in HR and [La-] as the physiological parameters and TWL as the perceptual parameter. Our data indicated that HR and [La-] gradually increased with trial distance.

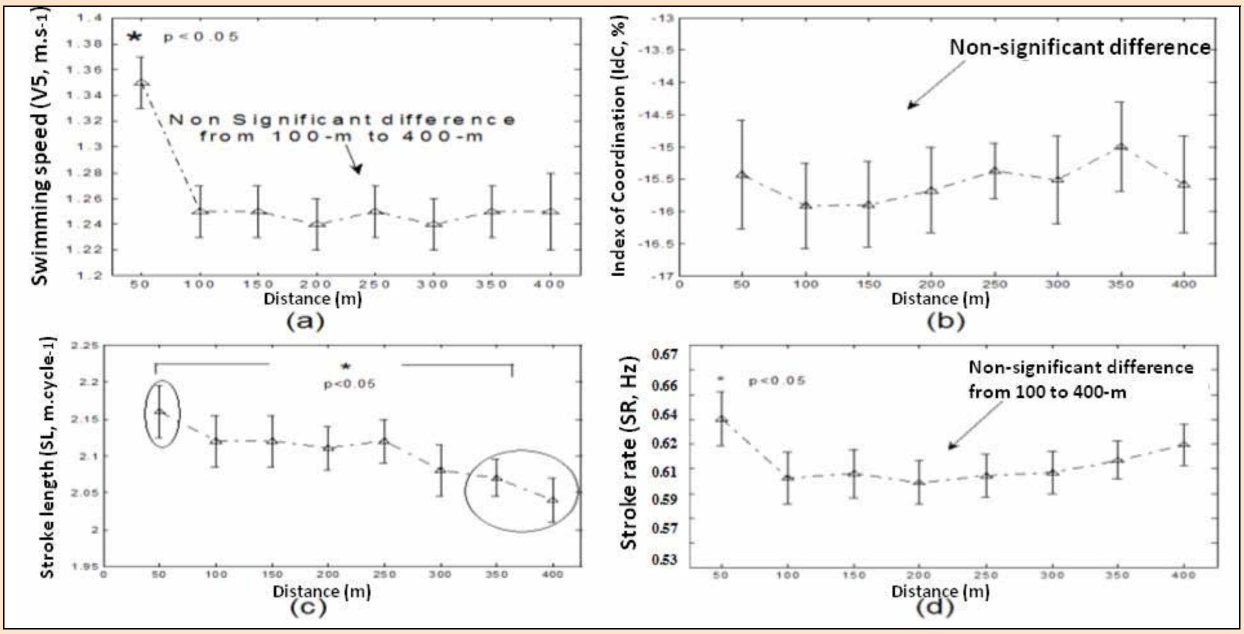

Figure 2. Inter-lap distance effect on kinematical and coordination parameters during the 400-m trial. (a) on swimming speed, (b) on Index of Coordination, (c) on stroke length, (d) on stroke.

The [La-] value is considered to be a reliable indicator of the contribution from the anaerobic pathways to total energy expenditure (Barbosa et al., 2006), and the maximal [La-] value has been associated with the impossibility to continue exercise (di Prampero, 1981; Gladden, 2001). According to Keskinen et al. (1988), the change in [La-] with distance indicates that swimmers pass progressively from medium intensity ([La-]<8mmol.l^{-1}) to high intensity ([La-]>8 mmol.l^{-1}), especially during the last 100-m. Together, the changes in HR and [La-] over the trial indicated that task difficulty increased with race distance. This conclusion was supported by the analysis of the swimmers' responses to the NASA-TLX questionnaire. Indeed, the perception of TWL increased progressively with trial distance, in accordance with previous results (Garcin and Billat, 2001). So even if the performance exhibited by the swimmers was far from its peak, the difficulty increased with distance from both physiological and psychological points of view, and could be linked to the appearance of fatigue.

Examination of the stroke cycle and coordination parameters showed that the women were characterised by lower mean speed, SL, IdC and propulsive phase duration (Ppr). These results are typical of inter-gender comparisons. More interesting was the absence of gender×distance interaction, which indicates that mixed-gender populations can be used to study variability in stroke cycle and coordination parameters.

The coefficients of variation for the stroke cycle and coordination parameters did not change significantly over trial distance, and their values (from 2.2% to 10.6%) were slightly lower than those of previous studies (Jeukendrup et al., 1996; McLellan et al., 1995) but close to the values reported in similar conditions (Alberty et al., 2006). The latter authors compared variability in three types of procedure: a constant distance test (400-m swum at maximal speed), a constant time test (maximal distance covered in 5 min), and a constant speed test until exhaustion. Their results suggested that test reliability improved when the end of the test was set beforehand, because constant speed tests were less reliable than constant distance and constant time tests. The testing in our study included a constant distance test, followed by three constant speed tests performed under submaximal conditions (since the swimmers were stopped before exhaustion). Here, no significant differences were found between coefficients of variation for any of the trial distances. However, one could object that inter-trial CV might be influenced by the fact that we had different value/do counts in each split. On the other hand, as CV was here directly sensitive to standard deviation (since velocity was the same between trials), a small variation in velocity would have an important impact on CV values for short distances (100-m) and would thus vary to a greater extent. But this is not the case, which suggests the conclusion that the inter-trial variability was not significant. Thus, despite the constant speed conditions, the reproducibility of the stroke cycle and coordination parameters was ensured, probably because the end of each test was set beforehand, as suggested by Alberty et al. (2006).

This conclusion was confirmed by the examination of the correlation coefficients across stroke cycle and coordination parameters. Our results indicated high retest correlation coefficients (0.87 ± 0.07), which did not differ between stroke cycle and coordination parameters.

These data thus confirmed that IdC and other stroke cycle phase measurements can be obtained on the basis of submaximal swim trials. This is important, since many experiments using IdC and stroke cycle phases have been based on this assumption (Chollet et al., 2000; Potdevin et al., 2005; Schnitzler et al., 2008; Seifert et al., 2004; Seifert et al., 2004; Seifert et al., 2007), which had not been previously tested. Stroke cycle and coordination parameters appear to be more sensitive to mean speed than to the expected magnitude of the effort to be performed.

Inter-lap variability of stroking and coordination parameters during the maximal 400-m swim trial

During the maximal 400-m swim, both V50 and SL decreased, whereas SR remained unchanged. These changes are typical of protocols performed under similar conditions (Laffite et al., 2004; Schnitzler et al., 2007). Meanwhile, no significant change in IdC was noted. This stability was also found for the stroke cycle phase (A, B, C, D, Ppr) durations.

This population was thus characterized by stable coordination parameters, despite increases in physiological and perceptual difficulty, and a change in stroke cycle parameters (V50 and SL). This suggests that changes in stroke cycle parameters are not only linked to coordination, but also to kinetic parameters. Toussaint et al. (2006) showed that during the four 25-m laps of a 100-m, the mechanical power output decreased, probably because of fatigue. Seifert et al., (2007) showed that IdC and the push phase durations both increased during the 100-m but were inefficient, since V and SL decreased. Our results demonstrated a decrease in V and SL but stability in IdC and the stroke cycle phases. This suggests that the variations might be better explained by a loss in power output consecutive to fatigue than by modifications in IdC and stroke cycle phases, although further investigation would be needed to prove this hypothesis. These results attest to the stability of the coordination parameters during a maximal 400-m swim despite an increase in fatigue. However, those data were obtained in training conditions, and thus they do not indicate that the race management used here is the best to optimize performance. Okuno et al. (2003) analyzed the 2001 world championship finals and observed that the finalists on average had behavior comparable to that of our group (a fast start followed by a stabilization of swimming speed), adopting a "neutral split approach" to race management. However, some cases of "positive split approach" (second part of the race faster than the first one) or, conversely, "negative split approach" were also reported (Okuno et al., 2003), with consecutive modification of SR and SL. These different race management approaches might have an effect on coordination parameters, but we did not distinguish between them in this study. So our results must be interpreted with caution and limited to middle- and long-distance swimmer who adopts a “neutral split approach”.

Conclusion

The combination of SL and IdC values is an interesting means to discriminate skill level (Chollet et al., 2000; Seifert et al., 2007). However, no study to date has investigated the inter-trial and inter-lap variability of coordination parameters for middle-distance events. Our study showed two important results: (i) experienced swimmers were able to reproduce not only stroke cycle but also coordination parameters at the 400-m pace, and (ii) despite the increase in fatigue during all-out 400-m freestyle swimming, coordination parameters remained stable. The small inter-trial and inter-lap variability of the parameters indicated that a protocol based on short swim trials swum at several race paces is appropriate to examine the stroke cycle and coordination parameters used in maximal testing conditions. This has important implications for swim testing in that it facilitates the examination of swimmers’ adaptation to different race distances, allowing procedures that are less time-consuming and thus with minor effects in the training process.

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Key points

- "During a maximal 400-m, fatigue led to an increase in both physiological (heart rate and blood lactate) and perceptual (subjective workload) parameters.
- The consequence was a decrease in stroke length and therefore in the swimming speed.
- However, inter-arm coordination did not change during this aerobic task.
- This indicates that inter-arm coordination can be examined on the basis of short-distance trials rather than on the full distance.

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