A New Index of Coordination for the Crawl: Description and Usefulness

D. Chollet[1], S. Chalies[1], J. C. Chatard[2]

[1] Faculté des Sciences du Sport, Université de Montpellier, France
[2] GIP Exercice, Faculté de Médecine, Université de Saint Etienne, France

Chollet D, Chalies S, Chatard JC. A New Index of Coordination for the Crawl: Description and Usefulness. Int J Sports Med 1999; 20: 54–59

Accepted after revision: July 15, 1999

This study analyzes stroke phases and arm and leg coordination during front crawl swimming as a function of swim velocity and performance level. Forty-three swimmers constituted three groups based on performance level. All swam at three different swim velocities, corresponding to the paces appropriate for the 800 m, 100 m, and 50 m. The different stroke phases and the arm and leg coordination were identified by video analysis. Arm coordination was quantified using a new index of coordination (IdC), which expresses the three major modalities opposition, catch-up and superposition. Opposition, where one arm begins the pull phase when the other is finishing the push phase; catch up, which has a lag time (LT) between propulsive phases of the two arms; and superposition, which describes an overlap in the propulsive phases. The IdC is an index which characterizes coordination patterns by measure of LT between propulsive phases of each arm. The most important results showed that duration of the propulsive phases (B + C) increased significantly with increasing velocity: 43.1 ± 3.3 % for V800; 46.5 ± 3 % for V100 and 49 ± 3 % for V50. The arm and leg synchronization was modified in the sense of an increase in six-beat kick. The IdC increased significantly with velocity: IdCV800 = – 7.6 ± 6.4 %; IdCV100 = – 3.2 ± 5.1 % and IdCV50 = – 0.9 ± 5.6 %. IdC increased also significantly with performance level: IdCG3 = – 6.07 ± 5.3 %; IdCG2 = – 3.9 ± 4.2 % and IdCG1 = – 1.76 ± 5.6 % for the mean of the 3 velocity. The two extreme IdC were IdCG3V800 = – 9.4 ± 5.4 % and IdCG1V50 = + 2.53 ± 4.4 %.

Key words: Motor coordination, biomechanics, performance, crawl, swimming.

Introduction

The coordination of arm movements during performance of the front crawl conforms to one of three major models [2,8]. The model of opposition describes a series of propulsive actions: one arm begins the pull phase when the other is finishing the push phase. The model of catch-up describes a lag time between the propulsive phases of the two arms. This lag generally occurs during the catch phase. Last, the superposition model describes an overlap, to a greater or lesser degree, in the propulsive phases [1] .

After the analysis of motor pattern of the crawl stroke in 1971 [14], no general method has yet been developed to quantify accurately the different types of coordination, except the model described by Chatard et al. [1]. There is, however, a clear need for such a tool. Indeed, Costill et al. [2] stated that the ideal coordination in high-level swimmers would conform to the opposition model. In theory, this mode of coordination provides continuous motor action and results in a smooth series of propulsive phases, without time lags. In contrast, Chatard et al. [1] suggested that the superposition model would be more economical in terms of energy cost. These authors demonstrated that the periods of simultaneous propulsion compensated for the non-propulsive lags time. The relative duration of the propulsive push and pull phases changes with swim velocity [2]. It also changes with the type of swimmer: sprint, middle-distance, or distance racers, and the type of leg kick: two-, four-, or six-beat kicks [8]. These changes occur at the expense of the non-propulsive phases of hand entry into the water and catch, and to recovery phase [1,9,10,13]. The organization of strokes is thus modified by numerous factors. However, no study has yet quantified accurately to what extent these factors modify coordination.

The major objective of this study was to describe a new tool, the Index of Coordination (IdC), to measure the coordination of arm stroking, with precise quantification of the lag time between the start of propulsion by one arm and the end of propulsion by the other. The second objective was to describe how this index varies as a function of swim velocity (velocities appropriate for the 800 m, 100 m, 50 m), performance level and the type of leg- arm synchronization.

Int J Sports Med 2000; 21: 54–59
© Georg Thieme Verlag Stuttgart · New York
ISSN 0172-4622

Material and Methods

Subjects

Forty-three French swimmers (29 boys, 14 girls), in national divisions 1, 2 or 3, gave informed written consent to participate in this study. They were assigned to one of three groups based on their performances in the 800 m, 100 m and the 50 m (Table **1**). The first group, G1, was composed of the 14 swimmers with the highest performances (10 boys and 4 girls). The third group, G3, was composed of the 14 swimmers with the lowest performances (9 boys and 5 girls). The middle group, G2, was composed of the 15 remaining intermediary performers (10 boys and 5 girls).

Swim trials

Each swimmer performed three swim trials in randomized order using the front crawl stroke. Each trial required a swim velocity corresponding to a specific race distance: the 800 m (V800), the 100 m (V100), and the 50 m (V50). The trials consisted of swimming at an imposed velocity in a 50 m pool while holding breath for a distance of 12.5 m (from 10 m to 22.5 m). Subjects were asked to hold their breath in order to avoid modifications in coordinations due to breathing. The rest period between each trial was at least 2 min 30 s. After each trial, the swimmer was informed of his or her performance. This performance was expected to be within ± 2.5 % of the subject's best performance for the three races distances. If this was not the case, the subject repeated the test.

Video analysis of arm and leg movements

The stroke phases and modes of arm and leg coordination (or synchronization) were analyzed underwater with two video cameras (S. VHS Panasonic) set at rapid shutter speed (1/1000 of a second); 50 pictures per second were filmed. One camera filmed the swimmer from a frontal view, the other in profile. They were connected to a double-entry audiovisual mixer, a chronometer, a monitoring screen and a video recorder that recorded the mixed picture (camera 1 in the upper half of the screen and camera 2 in the lower half, with the chronometer). A third independent camera filmed all trials of each swimmer in profile from above the pool. This camera allowed us to quantify the swim velocity and stroke rate, from which stroke length was calculated.

Coordination of arm movements

Arm coordination was quantified using the Index of Coordination (IdC). Each movement of the arm as recorded on video camera was broken down into four distinct phases (one phase corresponded to an action between two times), defined as follows:
Phase A: entry and catch of the hand in the water. This phase corresponded to the time from the hand's entry into the water to the beginning of its backwards movement.
Phase B: pull. This phase corresponded to the time from the beginning of the hand's backwards movement to the hand's arrival in the vertical plane to the shoulder. This phase was the beginning of propulsion.
Phase C: push. This phase corresponded to the time from the hand's position below the shoulder to its release from the water.
Phase D: recovery. This phase corresponded to the time from the hand's release from the water to its following entry into the water.

From this breakdown into distinct phases, the mean duration of each phase was calculated, with the chronometer and number of video picture (1 picture = 2/100 of a second), over a series of two arm strokes, or four complete movements. The mean duration of a complete arm movement, defined as the sum of the phases (A + B + C + D), was also calculated. Each phase was then expressed as a percentage of the duration of a total arm stroke.

In addition to the measurement of the stroke phases, the lag time (LT) between the propulsive movements of the left arm and the right arm was measured. LT corresponded to the time between the beginning of propulsion in the first right-arm stroke and the end of propulsion in the first left-arm stroke (LT1) and between the beginning of propulsion in the second left-arm stroke and the end of propulsion in the first right-arm stroke (LT2). LT1 and LT2 (Fig. **1**) were then each expressed as a percentage of the mean duration of a stroke cycle respectively IdC1 and IdC2. The Coordination Index (IdC) corresponded to the mean of the two indices (Fig. **1**).

Table 1 Principal characteristics of swimmers based on performance at an imposed swim velocity

SV	G	Age (yr)	Mass (kg)	Height (cm)	No. (ts/wk)	800 m Perf (s)	100 m Perf (s)
	G1	20.1 ± 3.2	69.8 ± 10.2	178.5 ± 7.7	7.1 ± 1.5	553.9 ± 36.8	56.76 ± 3.34
V800	G2	20.5 ± 3.8	67.9 ± 9.4	176.1 ± 5.8	5.2 ± 2.4	588.5 ± 14.8	58.56 ± 2.79
	G3	20.3 ± 2.8	67.5 ± 9.4	176.1 ± 7.6	4.4 ± 1.95	620.9 ± 33.4	60.19 ± 3.17
	G1	20.3 ± 3.4	68.9 ± 10.1	178.1 ± 5.9	5.9 ± 2	565.2 ± 40	56.01 ± 3.16
V100	G2	20.5 ± 3.6	67.9 ± 7.7	175.8 ± 5.8	5.1 ± 2.2	582.7 ± 31.4	58.66 ± 2.29
	G3	20 ± 2.7	68.4 ± 11.1	176.9 ± 9.3	4.8 ± 2.5	613.4 ± 36.8	60.7 ± 2.97
	G1	20.5 ± 3.9	71 ± 7.9	179.1 ± 5.7	5.7 ± 2.3	569.9 ± 40.7	56.27 ± 3.1
V50	G2	20.6 ± 2.9	67.6 ± 9.3	177 ± 6.1	5.2 ± 2	584.4 ± 34.5	58.59 ± 2.54
	G3	19.7 ± 2.8	66.4 ± 11.1	174.6 ± 8.7	4.9 ± 2.5	607.8 ± 38.8	60.68 ± 2.98

Abbreviations: SV: imposed swim velocity; G1: highest performers; G2: intermediate performes; G3: lowest performers; No. ts/wk: number of 2-hrs training sessions per week.

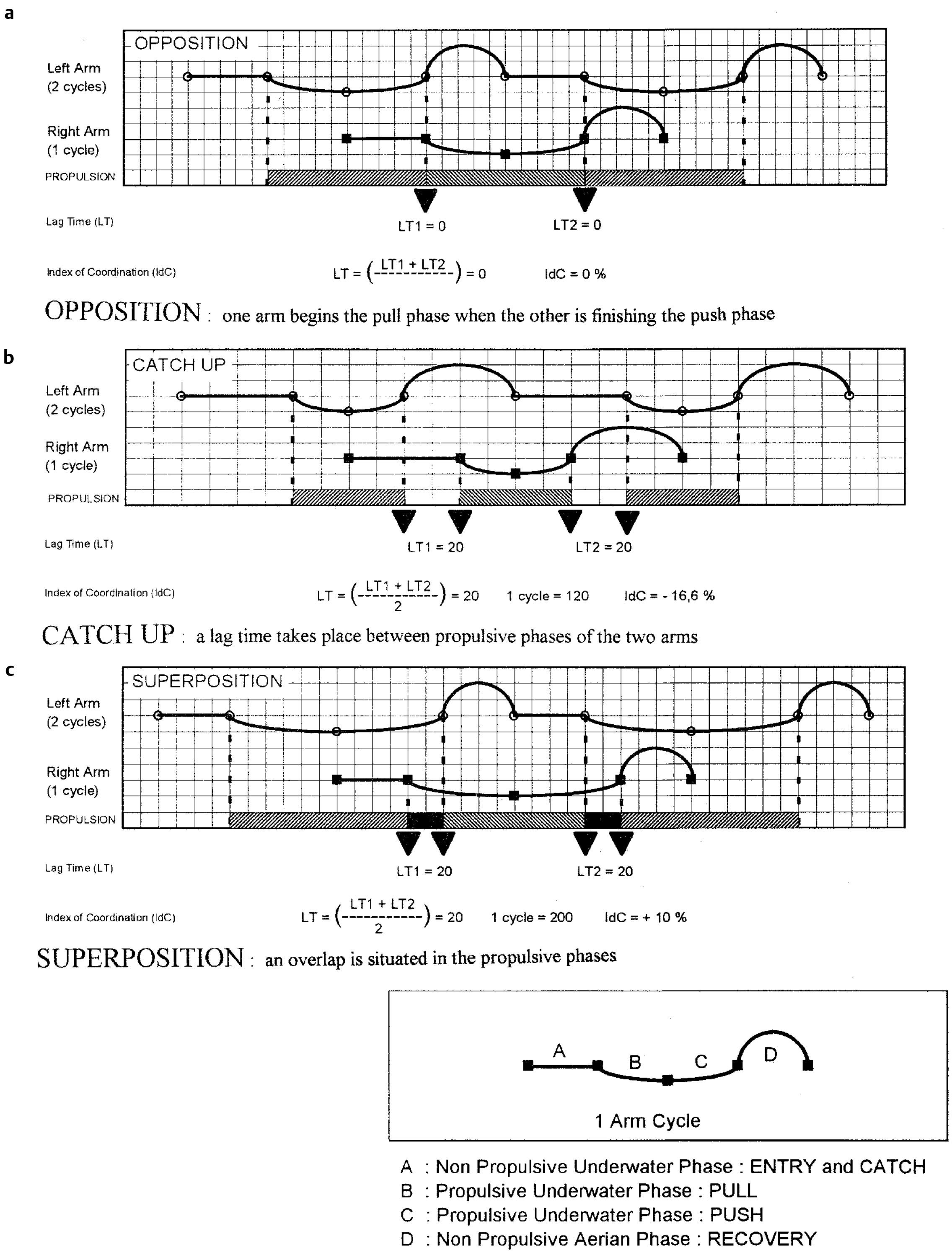

Fig. 1 Representation of the three models of stroke coordinations.

The stroke coordination at a given velocity that is defined by the catch up model may change to superposition with a change in velocity. The shift from one type of coordination to another is not a question of "all or nothing", but is in fact a progressive change that accompanies changes in velocity. The IdC is thus not only an index to characterize a given coordination pattern, but it also measures the coordination over time. Indeed, it can be compared to a sliding cursor on a numeric scale to illustrate the three principal modes of coordination between the two arms that were defined in the introduction. The IdC is null when coordination is said to be in opposition (Fig. **1 a**). This mode of coordination is characterized by uninterrupted propulsion between the two arms. The duration of the propulsive phases is equal to the duration of the non-propulsive phases. The IdC is negative when the coordination is said to be in catch-up (Fig. **1 b**). This mode of coordination is characterized by the presence of a non-propulsive lag time in the arm strokes. The IdC is positive when coordination is said to be in superposition of the propulsive action of the arms (Fig. **1 c**). This mode is characterized by a certain overlap in the propulsive phases of the two arms.

Synchronization of arm and leg movements

Synchronization using the six-beat kick was defined by the observation of three cycles of leg kicks (3 movements of legs ascending and 3 movements of legs descending, or a total of 6 movements) for a complete arm stroke. Synchronization using the four-beat kick was defined by observation of four leg kicks, and the synchronization of the two-beat kick was defined by the observation of two leg kicks for a complete arm stroke [2,8].

Statistical analysis

Comparison of the means was done with a two-way ANOVA (velocity for a given distance and performance level), each with three modalities, and this analysis was completed by the post-hoc test of Fisher. A chi 2 test (χ^2) compared the means for leg and arm synchronization with three modalities (two-, four-, or six-beat kick). Correlations were made between IdC and the other variables. All analyses were done using SYSTAT, and significance was fixed at the 0.05 level of confidence.

Results

For the entire population of swimmers, the mean IdC was negative: – 3.9 ± 6.3 %, in correspondence to catch up coordination. The relative duration of the underwater non-propulsive phase A (entry and catch) decreased significantly ($p < 0.05$) with the swim velocity and the performance level (Table **2**). In contrast, the duration of propulsive phases B and C (pull and push) was significantly ($p < 0.05$) increased (43.1 ± 3.3 % for V800; 46.5 ± 3 % for V100 and 49 ± 3 % for V50). The non-propulsive recovery phase D was not influenced by swim velocity, except for V800 and V100. There was no group effect.

IdC, stroke rate, stroke length and stroke phases

Tables **2** and **3** present the variations in IdC and the correlations with the swim velocities, performance levels, stroke rates, stroke lengths and stroke phases. IdC increased with swim velocity, performance level, and stroke rate, and decreased with stroke length. The relation between IdC and velocity can be showed: IdCV800 = – 7.6 ± 6.4 %; IdCV100 = – 3.2 ± 5.1 % and IdCV50 = – 0.9 ± 5.6 %. IdC increased also significantly with performance level: IdCG3 = – 6.07 ± 5.3 %; IdCG2 = – 3.9 ± 4.2 % and IdCG1 = – 1.76 ± 5.6 % for the mean of the 3 velocity. The two extreme IdC were IdCG3V800 = – 9.4 ± 5.4 % and IdCG1V50 = + 2.53 ± 4.4 %. IdC was inversely proportional to the duration of Phase A and was proportional to the duration of phases B and C. IdC thus increased in parallel with the duration of the propulsive phases at the expense of the underwater, non-propulsive phase (entry and catch). Its relationship with phase D was only significant in two out of the six situations studied (Table **3**).

Synchronization of arm and leg movements

The proportion of six-beat synchronization significantly increased with swim velocity and performance level. At V800, 16 % of the swimmers swam with two-beat synchronization,

Table 2 Mean (± SD) values of parameters in relationship to imposed swim velocity and performance level

SV	G	IdC (%)	V (m/s)	SR (stroke/min)	SL (m/stroke)	A (%)	B (%)	C (%)	D (%)
V800	G1	– 6.9 ± 7.1	1.49 ± 0.1	36.2 ± 3.1	2.47 ± 0.3	30.3 ± 6.5	21.3 ± 4.2	22.9 ± 2.7	25.5 ± 2.4
	G2	– 6.65 ± 3	1.4 ± 0.1 ★	33.8 ± 3.1	2.45 ± 0.3	31.3 ± 4.9	20.9 ± 2.6	23 ± 1.1	24.8 ± 2.9
	G3	– 9.4 ± 5.4	1.3 ± 0.1 ★/★★	31.7 ± 4.6 ★★	2.5 ± 0.3	34.3 ± 8	19.4 ± 5.2	21.5 ± 3.8	24.8 ± 3.4
	m	– 7.6 ± 6.4	1.4 ± 0.1	33.9 ± 3.6	2.47 ± 0.3	31.9 ± 6	20.6 ± 4	22.5 ± 2.5	25 ± 2.9
V100	G1	– 0.9 ± 5.4 ♦	1.76 ± 0.1 ♦	49.5 ± 4.3 ♦	2.15 ± 0.2 ♦	25.2 ± 5 ♦	23.4 ± 2.4	25.2 ± 3.5 ♦	26.2 ± 2.7
	G2	– 3.55 ± 4 ♦	1.65 ± 0.1 ♦/★	45.2 ± 3.7 ♦/★	2.22 ± 0.2 ♦	27.4 ± 4.1 ♦	22.7 ± 3.2 ♦	23.8 ± 2.6	26.1 ± 3
	G3	– 5.1 ± 5.4 ★★	1.6 ± 0.1 ♦/★/★★	44.8 ± 4.6 ♦/★★	2.15 ± 0.2 ♦	28.6 ± 4.3 ♦/★★	21.6 ± 3.4	22.9 ± 3 ★/★★	26.8 ± 3.5
	m	– 3.2 ± 5.1 ♦	1.67 ± 0.1 ♦	46.5 ± 4.2 ♦	2.17 ± 0.2 ♦	27.1 ± 4 ♦	22.6 ± 3 ♦	23.9 ± 3 ♦	26.4 ± 3.1 ♦
V50	G1	2.53 ± 4.4 ♦♦	1.81 ± 0.1 ♦/♦♦	54 ± 4 ♦/♦♦	2.01 ± 0.1 ♦/♦♦	22.1 ± 3.9 ♦♦	26.7 ± 3.7 ♦/♦♦	26.3 ± 2.7 ♦♦	24.9 ± 2.6
	G2	– 1.6 ± 5.7 ♦♦	1.75 ± 0.1 ♦/♦♦/★	51.6 ± 4.9 ♦/♦♦/★	2.03 ± 0.1 ♦/♦♦	24.7 ± 6 ♦♦	24.1 ± 3 ♦♦	24.6 ± 4.4	26.6 ± 1.9 ♦♦
	G3	– 3.7 ± 5 ♦♦ ★★	1.7 ± 0.1 ♦/♦♦ ★/★★	49.7 ± 5.8 ♦/♦♦ ★★	2 ± 0.2 ♦♦	26.7 ± 4.1 ♦♦ ★★	22.8 ± 3.3 ★★	23.1 ± 3.1 ★★	27.4 ± 4
	m	– 0.9 ± 5.6 ♦/♦♦	1.75 ± 0.1 ♦/♦♦	51.8 ± 4.9 ♦/♦♦	2.01 ± 0.1 ♦/♦♦	24.5 ± 5 ♦♦	24.5 ± 3 ♦♦	24.5 ± 3 ♦♦	26.3 ± 3 ♦♦
	M	– 3.9 ± 6.3	1.59 ± 0.2	44 ± 8.8	2.22 ± 0.3	27.9 ± 6.3	22.5 ± 3.9	23.7 ± 3.3	25.9 ± 3

Abbreviations: SV: imposed swim velocity; G1: highest performers; G2: intermediate performers; G3: lowest performers; SR: stroke rate; SL: stroke length; M: overall mean (m) of Gi + G2 + G3 for V800 + V100 + V50; A: entry and catch phase; B: pull phase; C: push phase; D: recovery phase; ♦: significant difference ($p < 0.05$) with preceding velocity; ♦♦ with V800; ★: significant difference ($p < 0.05$) with preceding group; ★★: with G1.

Table 3 Correlations between the Index of Coordination (IdC) and other parameters as a function of imposed swim velocity and performance level

	Velocity	Stroke rate	Stroke length	A entry + catch	B pull	C push	D recovery
IdC 800	NS	0.48	– 0.37	– 0.88	0.9	0.83	NS
IdC 100	NS	0.39	– 0.33	– 0.72	0.77	0.83	– 0.52
IdC 50	NS	NS	– 0.29	– 0.84	0.74	0.8	– 0.46
IdC G1	0.57	0.67	– 0.63	– 0.89	0.85	0.8	NS
IdC G2	0.53	0.65	– 0.29	– 0.82	0.71	0.78	NS
IdC G3	0.56	0.75	– 0.72	– 0.85	0.87	0.83	NS
Total IdC	0.41	0.54	– 0.52	– 0.86	0.84	0.81	NS

Abbreviations: G1: highest performers; G2: intermediate performers; G3: lowest performers; Total IdC: Index of Coordination for all swimmers (G1 + G2 + G3) at all paces (V800 + V100 + V50).

26% with four-beat, and 58% with six-beat. In contrast, at V50, none swam with two-beat synchronization, only 9% swam with four-beat, and 91% with six-beat. Synchronization with a six-beat kick was used by 86%, 82%, and 74% of the swimmers, respectively, for GI, G2, and G3, whereas synchronization with a four-beat kick was only used, respectively, by 9%, 14%, and 19%, and synchronization with the two-beat, by 5%, 4% and 7%.

Discussion

This study used a new index to measure the coordination of arm movements during performance of the front crawl. The principal results were that the IdC increased with swim velocity, performance level, and stroke rate. It also increased when stroke length decreased. These modifications specified as increases in the duration of the propulsive phases of stroking at the expense of the non-propulsive phases. The increase in IdC was associated with a change in arm-leg synchronization from a two-beat kick to a six-beat.

IdC, swim velocity, performance level, and stroke phases

IdC increased with the swim velocity. For the V800, a middle-distance pace, coordination conformed to the front catch-up model. In contrast, for the sprint (V100 and V50), coordination was accomplished by the opposition model. The swimmers reduced the non-propulsive phase of entry and catch during sprints and relatively increased the propulsive phases of pull and push. This finding agreed with the observations of Keskinen and Komi [5]. These authors showed in 10 high-level swimmers that the duration of the catch phase decreased with velocity between $1.1\,m \times s^{-1}$ and $1.8\,m \times s^{-1}$ whereas simultaneously the pull and push phases increased. These observations were also reported by Schleihauf et al. [12]. In making these adaptations, the swimmer is able to take advantage of longer periods of propulsive force application, thereby generating more power [1,3].

The increase in the relative duration of the two propulsive phases particularly concerned the pull phase, which increased more than the push phase. However, the modifications in the push phase were compensated for by acceleration of the hand. Indeed, this acceleration allows maximal velocity of hand displacement of about 80% at the end of its trajectory, i. e., in the middle of the push phase, and thus engenders a better propulsive action [3,11]. On average, the recovery phase slightly lengthened with swim velocity. This adaptation seemed to compensate in part for the shortening of the entry and catch phase. Furthermore, it allows an early start of the pull phase and a relatively longer muscular recovery time.

The changes in arm coordination as a function of velocity were further reinforced by the performance level. The higher the performance level, the more able the swimmers were to limit coordination by frontal catch-up which is characterized by a non-propulsive lag time and to take advantage of coordination in opposition or even in superposition to the arm action [7]. This last mode of coordination results in a better racing economy by reducing energy cost [1] and the hydrodynamic resistance [6]. Indeed, as Kolmogorov and Duplisheva [6] have specified, hydrodynamic resistance is directly dependent on swim technique. Thus, for example, the active drag may vary in the front crawl from 167 to 42 Newton as a function of the technique adopted [6].

The above-described adaptation was even more marked in the highest performing group, G1. They reduced more than the other two groups the non-propulsive phase of entry and catch and lengthened the propulsive phases of pull and push. In contrast to the mean for the entire population of swimmers, these swimmers decreased the recovery time when the velocity increased. This level of performance was thus characterized by the capacity to adapt technically [7] to the constraints, notably biomechanical, of the trials. These observations agree with those of Kolmogorov et al. [7], who showed in a diverse population of nearly 800 subjects, that the more accomplished swimmers are, the more they are able to reduce active drag by adapting their swim technique, and more specifically, by adapting the coordination of arm movements.

In this study, as the performance level rose the swimmers were more capable of increasing the propulsive phases of pull and push. When this increase was expressed in percentage, the G1 swimmers had a gain of nearly 40% as compared to 24.5% for the G3 group. Moreover, only G1 was able to decrease the relative length of the recovery phase (– 2.1% vs. + 10.5% for G3). High level swimmers are thus characterized by a greater capacity to modify the different phases of arm stroke.

Synchronization of arm and leg movements

An increase in swim velocity leads to modification in arm and leg synchronization, from a two-beat kick to six-beat kick. This finding explains a greater contribution of the legs directly to propulsion, and not only to the equilibration of the body in water [4]. Indeed, for these authors, the use of the six-beat kick increases the maximal swim velocity by 4%, i.e., an increase from 1.72 $m \times s^{-1}$ to 1.79 $m \times s^{-1}$.

These modifications of leg and arm synchronization seemed independent of the modifications specific to arm movement. Indeed, the better the swimmers were, the more able were they to modify arm coordination with increases in velocity (from IdC for V800 = – 6.9% to IdC for V50 = + 2.53%), while maintaining their arm and leg synchronization stable (71.5% of the swimmers performed the six-beat kick at V800 and 93% at V50). In contrast, the least performing swimmers modified arm coordination very little (IdC for V800 = – 7.6% to IdC for V50 = – 3.7%) and were unable to maintain the stability of their arm and leg synchronization (35.7% used the six-beat kick at V800 and 93% at V50).

Conclusion

Swimmers modified their arm coordination with increases in velocity and as a function of performance level. They changed from a coordination mode of frontal catch-up in the middle-distance trial to coordination in opposition or superposition in the sprint trial. Using the new Index of Coordination, it was demonstrated that these changes reflected changes in the organization of the stroking phases. Propulsive phases increased at the expense of the non-propulsive phases. The Index of Coordination allows the precise quantification of the mode of arm coordination, and provides an indication of the technical skill of the swimmer.

References

1 Chatard JC, Collomp C, Maglischo E, Maglischo C. Swimming skill and stroking characteristics of front crawl swimmers. Int J Sports Med 1990; 11: 156 – 161
2 Costill DL, Maglischo EW, Richardson AB. Swimming. Oxford: Blackwell Scientific Publications, 1992
3 Counsilman JE. Hand speed and acceleration. Swimming technique 1981; 18: 22 – 26
4 Hollander AP, De Groot G, Van Ingen Schenau GJ, Kahman R, Toussaint HM. Contribution of the legs to propulsion in front crawl swimming. In: Ungerechts BE, Wilke K, Reischle K (eds). Swimming Science V. Champaign, IL: Human Kinetics Publishers, 1988: 39 – 44
5 Keskinen KL, Komi PV. Stroking characteristics of front crawl swimming during exercise. J Appl Biomech 1993; 9: 219 – 226
6 Kolmogorov SV, Duplisheva A. Active drug, useful mechanical power output and hydrodynamic force coefficient in different swimming strokes at maximal velocity. J Biomech 1992; 25: 311 – 318
7 Kolmogorov SV, Rumyantseva OA, Gordon BJ, Cappaert JM. Hydrodynamic characteristics of competitive swimmers of different genders and performance levels. J Appl Biomech 1997; 13: 88 – 97
8 Maglischo EW. Swimming Even Faster. Montain View, CA: Mayfield Publishing Company, 1993: 363 – 388
9 Maglischo CW, Maglischo EW, Higgins J, Luedtke D, Schleihauf RE, Thayer A. A biomechanical analysis of the U.S. Olympic freestyle distance swimmers. In: Ungerechts BE, Wilke K, Reischle K (eds). Swimming Science V. Champaign, IL: Human Kinetics Publishers, 1988: 351 – 359
10 Monteil KM, Rouard AH, Dufour AB, Cappaert JM, Troup JP. Front crawl stroke phases: discriminating kinematic and kinetic parameters. In: Troup JP, Hollander AP, Strass D, Trappe SW, Cappaert JM, Trappe TA (eds). Biomechanics and medicine in swimming VII. London: E & FN Spon, 1996: 44 – 50
11 Rouard AH, Billat RP. Influence of sex and level of performance on freestyle stroke: an electromyography and kinematic study. Int J Sport Med 1990; 11: 150 – 155
12 Schleihauf RE, Higgins J, Hinricks R, Luedtke D, Maglischo CW, Maglischo EW, Thayer A. Models of aquatic skill in sprint front crawl stroke. NZ J Sports Med 1986; 14: 7 – 12
13 Toussaint HM, Beek PJ. Biomechanics of competitive front crawl swimming. Sport Med 1992; 13: 8 – 24
14 Vaday M, Nemessuri M. Motor pattern of free-style swimming. In: Lewillie L, Clarys JP (eds). Biomechanics in swimming I. Bruxelles: Université Libre de Bruxelles, 1971: 167 – 173

Corresponding Author:

Pr. Didier Chollet, Ph.D.

Faculté des Sciences du Sport
Université de Montpellier
700 Avenue du Pic St. Loup
F-34090 Montpellier
France

Phone: + 33 (467) 415 749
Fax: + 33 (467) 415 709
E-mail: chollet@sc.univ-montp1.fr