

# Kinematic Changes during a 100-m Front Crawl: Effects of Performance Level and Gender

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## ABSTRACT

SEIFERT, L., D. CHOLLET, and J. C. CHATARD. Kinematic Changes during a 100-m Front Crawl: Effects of Performance Level and Gender. *Med. Sci. Sports Exerc.*, Vol. 39, No. 10, pp. 1784–1793, 2007. **Purpose:** This study analyzed kinematic changes during a 100-m front crawl to investigate the effects of performance level and gender, comparing 12 high-speed males, 8 medium-speed males, 8 low-speed males, and 8 high-speed females. **Methods:** Assessments were made throughout the race in a 25-m pool divided into five zones of 5 m. Velocity ( $V$ ), stroke rate (SR), and stroke length (SL) were calculated for each 25-m length (L1 to L4) and for each 5-m zone. Four stroke phases were identified by video analysis, and the index of coordination (IdC) was calculated. Three modes of arm coordination were identified: catch-up, opposition, and superposition. The leg kick was also analyzed. **Results:** The high-speed male swimmers were distinguished by higher  $V$  ( $1.89 \text{ m}\cdot\text{s}^{-1}$ ), SR (0.78 Hz), SL (2.16 m per stroke), propulsive phase (54%), and IdC (3.8%) ( $P < 0.05$ ), and by the stability of these values throughout the race. The medium- and low-speed males had an opposition coordination ( $-1\% < \text{IdC} < 1\%$ ) during the third length of the 100 m. Because of fatigue in length 4, they spent more time with the hand in the push phase (possibly because of a decrease in hand velocity) and changed to superposition coordination (medium-speed males: IdC = 2.78%; low-speed males: IdC = 1.12%) ( $P < 0.05$ ). This change was ineffective, however, as SL continued to decrease throughout the 100 m ( $P < 0.05$ ). The main gender findings were the greater SL of the males versus the females (1.81 m per stroke) ( $P < 0.05$ ) and the similar IdC of both high-speed groups (females: 4.4%). **Conclusion:** The high-speed swimmers were characterized by higher and more stable SL and IdC. The principal gender effect was greater SL in the males than in the females. **Key Words:** BIOMECHANICS, MOTOR CONTROL, RACE ANALYSES, SWIMMING

Performance (assessed by velocity ( $V$ )) in a 100-m freestyle depends on race management (15,17) and fatigue (28), from which results an optimal stroke length (SL)/stroke rate (SR) ratio (2,7,18). High-speed swimmers are characterized by longer and more stable SL than other swimmers (5). They maintain long SL into the second part of the race (8,28), whereas SR is mostly responsible for the performance changes in the first part of the race. The gender effect is characterized by higher performance for males than for females, attributable to greater SL for males but similar SR (2,10,18,19). For a similar performance ( $V$ ), a higher power output is developed by the males, whereas a lower drag is observed for the females. Indeed, drag =  $30V^2$  for males versus drag =  $24V^2$

for females (29). The power developed per cycle for males relative to their drag value is, thus, greater than that for females (assuming equal propelling efficiency), leading to longer SL for the males. The difference in body cross-sectional area, height, and buoyancy between males and females (29) may explain the lower drag of the females. This has led many studies (2,10,17,18) to relate the shorter SL of females to their lower values for height, arm span, and leg and arm lengths. Grimston and Hay (10) found that for both genders, 6 of 21 parameters (axilla, hand and foot cross-sectional areas, leg frontal area, and leg and arm lengths) have a significant influence on SL, SR, and  $V$ .

Performance ( $V$ ) contributes to the determination of the mode of interarm coordination (4,20,23,24), the leg beat kick (4,16,19), and the coordination between breathing and arm-stroke phases (14). To measure interarm coordination, Chollet et al. (4) created an index of coordination (IdC) based on the four arm-stroke phases (entry, pull, push, and recovery). This interarm coordination is influenced by environmental constraints (e.g., active drag and  $V$ ) (24), so that high-speed swimmers can adopt a more streamlined position than others, sometimes showing lower active drag than passive drag (13). Because high active drag must be overcome by very fast swimming, high-speed swimmers have a higher IdC (i.e., higher superposition of both arm

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cycles) than do low-speed swimmers (3,4,14), which is related to the smaller relative duration of the entry phase and to the larger relative duration of the pull and push phases (4,12,27).

The interarm coordination is also determined by the task constraints (pace imposed, goal, instructions, or rules of the task, notably adopting an imposed SR) (24). From middle distance to sprint pace, interarm coordination switches from catch-up to relative opposition–superposition coordination (4,24).

The third type of constraints that influence interarm coordination is the organismic constraints (24): the swimmer’s specialty (middle distance vs sprint (24); swimmers vs triathletes (16)), propulsive ability (27), anthropometric properties (arm span, height, and foot and arm length) (20,24), and gender (difference between males and females) (23). The interarm coordination of male swimmers reveals greater superposition of the arm propulsion and, therefore, better continuity of these actions than that of their female counterparts (23).

In the 100-m event, elite male swimmers show high SL and IdC, which tend to remain constant throughout the race (22). Elite male swimmers mainly use a six-beat leg kick during the 100 m (19,22). However, no study has ever measured the modifications in interarm coordination and leg kick through the course of 100 m in both males and females. Inter- and intralength comparisons (for the four 25-m lengths of the 100-m swim) would be a useful means to determine whether SL, SR, and interarm coordination and leg kick are more stable in high-speed swimmers (22) than in other swimmers.

Thus, the aim of this study was to compare the changes in *V*, SL, SR, and interarm coordination and the leg kick throughout a 100-m front crawl in high-, medium- and low-speed swimmers and between males and females. It was hypothesized that 1) the high-speed swimmers would be characterized by higher *V*, SL, SR, and coordination (IdC) values and by the stability of these values throughout the race, and 2) the males would have higher *V*, SL, and SR values than the females.

**METHOD**

**Subjects.** Thirty-six swimmers volunteered to participate in this study and were assigned to one of four groups according to performance level and gender. Their main characteristics are summarized in Table 1. The performance level was based on the personal time record for a 100-m front crawl and is expressed as a percentage of the 100-m world record (% of WR) by dividing the person’s average speed during the 100 m by the WR average speed during 100 m. G1 was composed of 12 high-speed males (close to 90% of WR) and included one Olympic Games finalist, one European Junior Champion, and international and/or national swimmers. G2 was composed of eight medium-speed males (close to 80% of WR) corresponding

TABLE 1. Anthropometric and performance data of the four groups of swimmers.

Groups	Age (yr)		Mass (kg)		Height (m)		Arm Span (m)		Foot Length (m)		Hand Length (m)		Time on 100 m (s)		(% of World Record)	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
G1: high-speed males	19.8	3.1	76.4	5.5 <sup>d</sup>	1.83	0.05 <sup>d</sup>	1.90	0.07 <sup>d</sup>	0.271	0.008 <sup>d</sup>	0.192	0.01 <sup>d</sup>	53.4	3.2 <sup>b,c,d</sup>	88.4	5.2 <sup>b,c</sup>
G2: medium-speed males	20.9	1.1	71.2	7.1 <sup>d</sup>	1.77	0.05 <sup>d</sup>	1.82	0.07 <sup>d</sup>	0.257	0.012 <sup>d</sup>	0.188	0.012 <sup>d</sup>	58.9	1.3 <sup>a,c</sup>	79.3	1.7 <sup>a,c,d</sup>
G3: low-speed males	20.1	1.6	70.6	5.2 <sup>d</sup>	1.79	0.06 <sup>d</sup>	1.85	0.08 <sup>d</sup>	0.264	0.012 <sup>d</sup>	0.184	0.006 <sup>d</sup>	67.3	3.1 <sup>a,b,d</sup>	69.6	3.1 <sup>a,b,d</sup>
G4: high-speed females	20.6	1.9	57.4	5 <sup>a,b,c</sup>	1.65	0.04 <sup>a,b,c</sup>	1.68	0.04 <sup>a,b,c</sup>	0.233	0.008 <sup>a,b,c</sup>	0.167	0.008 <sup>a,b,c</sup>	61.9	1.9 <sup>a,c</sup>	84.4	2.6 <sup>b,c</sup>

<sup>a</sup> Significantly different from G1; <sup>b</sup> Significantly different from G2; <sup>c</sup> Significantly different from G3; <sup>d</sup> Significantly different from G4 (*P* < 0.05).

to regional swimmers, G3 of eight low-speed males (close to 70% of WR) corresponding to swimming specialist students at the University of Sports Sciences, and G4 of eight high-speed females (close to 90% of WR), including national and/or international swimmers. The protocol, approved by the university ethics committee, was explained to the swimmers, who then gave their written consent to participate.

**Swim trials.** Each swimmer performed a 100-m front crawl in a 25-m pool. The intensity of the 100-m crawl was expected to be as close as possible to that of a real competition. For each swimmer, the best time of the season was used to estimate the performance level as regards the time ranking fixed by the French Swimming Federation.

**Video analysis.** Two underwater video cameras (Sony compact FCB-EX10L, 50 Hz) with rapid shutter speed (1/1000 s) were fixed on a trolley to film the swimmers along the right and left sides of the pool. The trolleys were pulled by an operator at the swimmer's head level at the same velocity as the swimmers to avoid parallax errors. The cameras were connected to a double-entry audiovisual mixer, a video recorder, and a monitoring screen. A video timer helped to mix the right and left lateral views on the same screen, following a protocol already described (4,22).

A third synchronized video camera filmed the 100-m swim from a profile view above the pool. It visualized the entire 25-m length of the pool on the video screen and helped in the analysis of the four *interlength* comparisons (L1, L2, L3, L4). Four plots delimited the 5-, 10-, 15- and 20-m marks on the right and left sides of the pool. They delimited five 5-m lengths or zones (Z1, Z2, Z3, Z4, Z5) used for *intra*length comparisons, as previously done (22).  $V$  was calculated for each 5-m zone from the swimmer's head in meters per second. SR in hertz was calculated from the duration of each stroke, which was timed with the video timer from the entry of the left hand at the first stroke to entry of the left hand at the first stroke. Each 5-m zone contained two or three arm-stroke cycles. The arm-stroke cycle was considered to be in a zone when the swimmer's head was in the zone. Some cycles were in two zones. In these cases, the relative duration spent in each zone

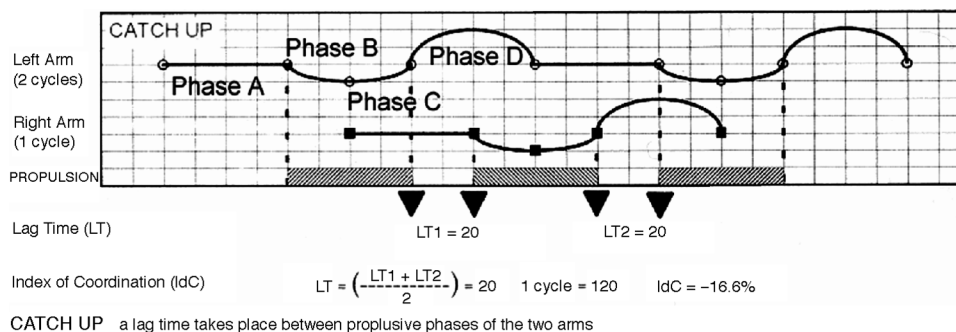
determined the zone in which the stroke was taken into account. SL was calculated in meters per stroke, from  $V$  and SR for each cycle, using the equation (1):

$$SL = V/SR \quad [1]$$

Because of the diving start in Z1 of L1 and the push after the turn-out in Z1 of L2, L3, and L4, no arm-stroke cycle was measured in Z1. Therefore, only  $V$  was measured in Z1. SR and SL were thus calculated from the number of arm-stroke cycles per swim zone (Z2–Z5) and per the four 25-m lengths of the 100 m (L1, L2, L3, L4). For Z5, the head did not cover the complete 5-m distance because, at L1, L2, and L3, the swimmers turned and touched the wall with their feet and, at L4, they stretched their arms to the wall. Therefore, for L1, L2, and L3, the duration of Z5 was calculated from the head passing at 20 m to the feet touching the wall. For L4, the duration of Z5 was calculated from the head passing at 20 m to the hand touching the wall, which slightly overestimated  $V$ .

**Coordination of arm movements.** Four arm phases were determined (Fig. 1). *Phase A*: entry and catch of the hand in the water. This corresponded to the time from the hand's entry into the water to the maximal forward coordinate of the hand, which also marked the beginning of its backward movement. *Phase B*: pull. This corresponded to the time from the beginning of the hand's backward movement to the hand's arrival in the vertical plane to the shoulder. This phase was the beginning of the propulsion. *Phase C*: push. This corresponded to the time from the hand's position below the shoulder to its release from the water. *Phase D*: recovery. This corresponded to the time from the hand's release from the water to its following entry into the water.

The key motor points of the arm phase was subjectively determined by three independent operators measuring, as previously described (4), every 0.02 s with a blind technique—that is, without knowing the results of the analyses of the two other operators. The three analyses were then compared. When the differences between the three video analyses were < 0.04 s, the mean of the analyses was accepted to validate the key points. When the error was > 0.04 s, the three operators proceeded to a new assessment of the key points.



**FIGURE 1**—Example of arm–arm catch-up coordination and details of the four arm-stroke phases (phase A = entry, phase B = pull, phase C = push, phase D = recovery).

TABLE 2. Statistics of the three-way analysis of variance for mixed-effect linear models.

	Group	Length	Group × Length	Group × Zone (Length)	Zone (Length)
Velocity	$F_{3,640} = 244.2$	$F_{3,640} = 244.1$	$F_{9,640} = 5.8$	$F_{48,640} = 2.7$	$F_{16,640} = 379.6$
Stroke rate	$F_{3,496} = 26.0$	$F_{3,496} = 102.1$	$F_{9,496} = 7.6$	NS	$F_{12,496} = 2.5$
Stroke length	$F_{3,496} = 100.2$	$F_{3,496} = 2.9$	$F_{9,496} = 2.9$	$F_{36,496} = 1.48$	$F_{12,496} = 11.2$
IdC	$F_{3,496} = 37.5$	$F_{3,496} = 5.9$	$F_{9,496} = 3$	NS	$F_{12,496} = 2.2$
Phase A	$F_{3,496} = 47.2$	$F_{3,496} = 7.4$	NS	NS	NS
Phase B	$F_{3,496} = 72.3$	$F_{3,496} = 7.1$	NS	NS	NS
Phase C	$F_{3,496} = 6.6$	$F_{3,496} = 4.9$	$F_{9,496} = 2$	NS	NS
Phase D	$F_{3,496} = 21.2$	$F_{3,496} = 18.4$	NS	NS	NS
Propulsive phase	$F_{3,496} = 42.5$	$F_{3,496} = 4.7$	$F_{9,496} = 1.9$	NS	$F_{12,496} = 2.5$
Nonpropulsive phase	$F_{3,496} = 34.7$	$F_{3,496} = 5.4$	NS	NS	$F_{12,496} = 2.6$

Effects of group (fixed factor), length (fixed factor), and zone (random factor embedded in length factor) for each variable. Significant at  $P < 0.05$ . NS, nonsignificant.  $N = 720$  for velocity;  $N = 560$  for the other variables.

The duration of each phase was measured for each arm-stroke cycle with a precision of 0.02 s (50 Hz) and was expressed as a percentage of the duration of the complete arm-stroke cycle. The duration of the propulsive phases was the sum of phases B and C. The duration of the nonpropulsive phases was the sum of phases A and D. The duration of a complete arm-stroke cycle was the sum of the propulsive and nonpropulsive phases (equation 2).

$$\text{Duration}_{\text{Complete cycle}} = ((\text{phase A} + \text{phase B} + \text{phase C} + \text{phase D})_{\text{left arm}} + (\text{phase A} + \text{phase B} + \text{phase C} + \text{phase D})_{\text{right arm}}) / 2 \quad [2]$$

The IdC calculated the time gap between the propulsion of the two arms as a percentage of the duration of the complete arm-stroke cycle. IdC was the mean of IdC<sub>left</sub> (equation 3) and IdC<sub>right</sub> (equation 4):

$$\text{IdC}_{\text{left}} = ((\text{Time}_{\text{End of phase C for left arm}} - \text{Time}_{\text{Beginning of phase B for right arm}}) \times 100) / \text{Duration}_{\text{Complete cycle}} \quad [3]$$

$$\text{IdC}_{\text{right}} = ((\text{Time}_{\text{End of phase C for right arm}} - \text{Time}_{\text{Beginning of phase B for left arm}}) \times 100) / \text{Duration}_{\text{Complete cycle}} \quad [4]$$

When IdC was  $< 0\%$ , the arm coordination was called *catch-up* coordination because there was a lag time between the propulsive phases of the two arms. When the propulsive

TABLE 3. Differences in index of coordination (IdC), velocity (V), stroke rate (SR), and stroke length (SL) among the four groups for the mean of the 100 m and for each length.

	Length 1		Length 2		Length 3		Length 4		100 m	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
G1										
IdC	5.23	3.43 <sup>b,c</sup>	2.67	3.96 <sup>b,c</sup>	3.85	3.65 <sup>b,c</sup>	3.76	3.69 <sup>c</sup>	3.8	3.8 <sup>b,c</sup>
Velocity (m·s <sup>-1</sup> )	2.11	0.61 <sup>b,c,d</sup>	1.87	0.4 <sup>b,c,d</sup>	1.8	0.49 <sup>b,c,d</sup>	1.77	0.36 <sup>b,c,d</sup>	1.89	0.49 <sup>b,c,d</sup>
Stroke rate (Hz)	0.86	0.05 <sup>b,c</sup>	0.78	0.04 <sup>c</sup>	0.74	0.05 <sup>c</sup>	0.73	0.04 <sup>c</sup>	0.78	0.06 <sup>c</sup>
Stroke length (meters per stroke)	2.13	0.2 <sup>b,c,d</sup>	2.17	0.16 <sup>b,c,d</sup>	2.15	0.18 <sup>b,c,d</sup>	2.18	0.18 <sup>b,c,d</sup>	2.16	0.18 <sup>b,c,d</sup>
IdC	0.27	3.89 <sup>a,d</sup>	-0.12	3.97 <sup>a,d</sup>	0.84	4.33 <sup>a,d</sup>	2.78	4.56 <sup>c,d</sup>	1	4.3 <sup>a,c,d</sup>
G2										
Velocity (m·s <sup>-1</sup> )	1.94	0.58 <sup>a,c,d</sup>	1.71	0.35 <sup>a,c,d</sup>	1.66	0.45 <sup>a,c,d</sup>	1.59	0.3 <sup>a,c,d</sup>	1.73	0.45 <sup>a,c,d</sup>
Stroke rate (Hz)	0.84	0.05 <sup>a,c,d</sup>	0.79	0.05 <sup>c</sup>	0.76	0.05 <sup>c</sup>	0.74	0.05 <sup>c,d</sup>	0.78	0.06 <sup>c</sup>
Stroke length (meters per stroke)	2.01	0.13 <sup>a,d</sup>	1.97	0.16 <sup>a,d</sup>	1.92	0.16 <sup>a,d</sup>	1.93	0.21 <sup>a,c,d</sup>	1.96	0.17 <sup>a,c,d</sup>
IdC	-0.03	3.83 <sup>a,d</sup>	-1.2	4.25 <sup>a,d</sup>	-0.08	4.34 <sup>a,d</sup>	1.12	4.83 <sup>a,b,d</sup>	0	4.4 <sup>a,b,d</sup>
G3										
Velocity (m·s <sup>-1</sup> )	1.85	0.69 <sup>a,b</sup>	1.52	0.31 <sup>a,b,d</sup>	1.45	0.33 <sup>a,b</sup>	1.41	0.29 <sup>a,b,d</sup>	1.55	0.47 <sup>a,b</sup>
Stroke rate (Hz)	0.79	0.06 <sup>a,b,d</sup>	0.72	0.04	0.7	0.04	0.7	0.03 <sup>a,b,d</sup>	0.73	0.06 <sup>a,b,d</sup>
Stroke length (meters per stroke)	1.95	0.21 <sup>a,d</sup>	1.95	0.15 <sup>a,d</sup>	1.87	0.19 <sup>a,d</sup>	1.81	0.16 <sup>a,b</sup>	1.89	0.19 <sup>a,b,d</sup>
IdC	4.54	4.79 <sup>b,c</sup>	3.37	4.27 <sup>b,c</sup>	4.67	4 <sup>b,c</sup>	4.92	4.3 <sup>b,c</sup>	4.4	4.4 <sup>b,c</sup>
G4										
Velocity (m·s <sup>-1</sup> )	1.8	0.56 <sup>a,b</sup>	1.56	0.3 <sup>a,b,d</sup>	1.51	0.39 <sup>a,b</sup>	1.46	0.3 <sup>a,b,d</sup>	1.58	0.42 <sup>a,b</sup>
Stroke rate (Hz)	0.86	0.09 <sup>b,c</sup>	0.79	0.08 <sup>c</sup>	0.75	0.08 <sup>c</sup>	0.73	0.07 <sup>b,c</sup>	0.78	0.09 <sup>c</sup>
Stroke length (meters per stroke)	1.82	0.2 <sup>a,b,c</sup>	1.84	0.2 <sup>a,b,c</sup>	1.78	0.2 <sup>a,b,c</sup>	1.81	0.24 <sup>a,b</sup>	1.81	0.21 <sup>a,b,c</sup>
IdC	2.67	4.66	1.32	4.5	2.44	4.51	3.18	4.53	2.42	4.59
Mean group										
Velocity (m·s <sup>-1</sup> )	1.95	0.62	1.69	0.38	1.63	0.45	1.58	0.35	1.71	0.48
Stroke rate (Hz)	0.84	0.07	0.77	0.06	0.74	0.06	0.72	0.05	0.76	0.08
Stroke length (meters per stroke)	1.98	0.22	1.99	0.21	1.94	0.22	1.94	0.25	1.96	0.23

IdC, percentage of an arm-stroke cycle. V was calculated from the five 5-m zones (zones 1–5), whereas IdC, SR, and SL were calculated from the four swim zones (zones 2–5). G1, high-speed males; G2, medium-speed males; G3, low-speed males; G4, high-speed females. <sup>a</sup> Significantly different from G1; <sup>b</sup> significantly different from G2; <sup>c</sup> significantly different from G3; <sup>d</sup> significantly different from G4 ( $P < 0.05$ ).

phase of one arm started at the time the other arm finished its propulsive phase, the coordination was called *opposition* ( $\text{IdC} = 0\%$ ). In fact, the opposition coordination for  $\text{IdC} = 0$  is theoretical; in practical terms, the opposition coordination is accepted for  $-1\% < \text{IdC} < 1\%$ . When the propulsive phases of the two arms overlapped, the coordination was called *superposition* ( $\text{IdC} > 0\%$ ).

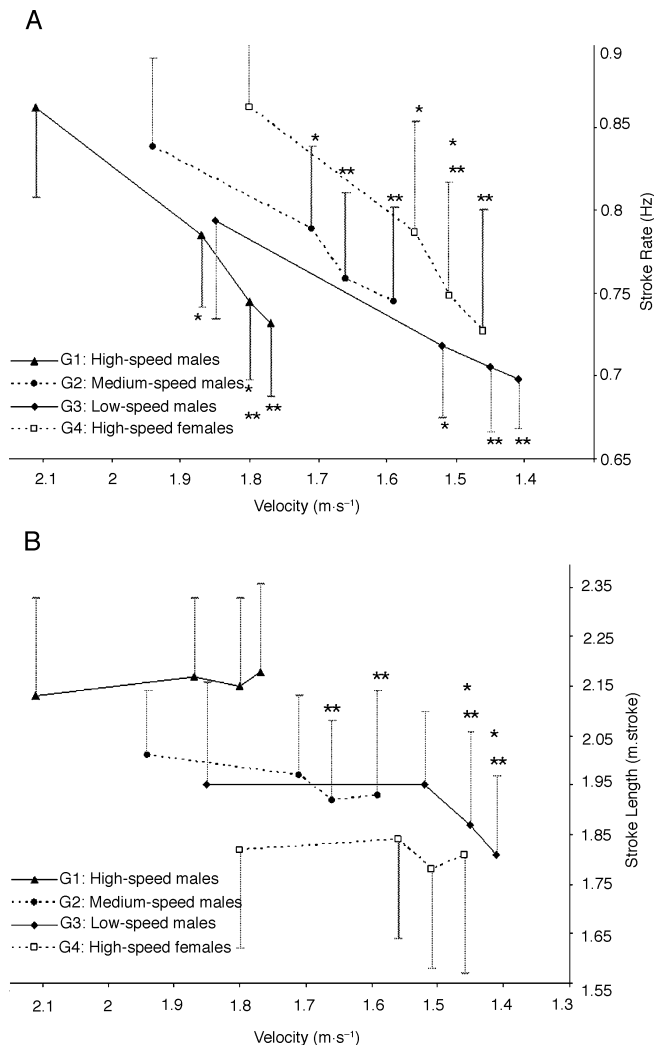
**Statistical analysis.** Before using parametric statistics (Minitab 14.10, Minitab, Inc., 2003), the normal distribution (Ryan–Joiner test, equivalent to the Shapiro–Francia test) and the homogeneity of variance (Bartlett test) were controlled for each variable in the whole population and the four groups of swimmers. A three-way analysis of variance was completed by *post hoc* Tukey tests to determine differences within groups. For all tests, the level of significance was set at 0.05. The *group* factor (four groups) was crossed with the *length* factor (four 25 m) and the *zone* factor. The zone factor was a random factor that was embedded in the length factor and crossed with the group factor; it presented five levels for  $V$  and four levels for the other variables. One-way analysis of variance analyzed the swimmers' characteristics and anthropometric data (Table 1); then, the Pearson correlation test analyzed the relationships between the anthropometric data and SL.

## RESULTS

The three groups of males were significantly taller and heavier than the females and had significantly greater arm span, foot length, and hand length ( $P < 0.05$ ) (Table 1). SL was significantly correlated with height ( $r = 0.385$ ), arm span ( $r = 0.366$ ), foot length ( $r = 0.507$ ), and hand length ( $r = 0.378$ ) ( $P < 0.05$ ). The results of the three-way analysis showed significant differences of IdC,  $V$ , SR, and SL for speed group, length, and zone (Table 2).

**V, SR, SL.** G1 and G2 had significantly higher  $V$  than G3 and G4, and the  $V$  of G1 was also significantly higher than that of G2 ( $P < 0.05$ ) (Table 3). G1 had significantly higher SR than G3 and significantly greater SL than G2, G3, and G4 ( $P < 0.05$ ) (Table 3).  $V$  declined significantly during the four 25-m lengths ( $P < 0.05$ ), corresponding to a decrease of 16.1% for G1, 18% for G2, 23.8% for G3, and 18.9% for G4 from L1 to L4. Only the high-speed male and female swimmers (G1 and G4) showed a nonsignificant decrease in  $V$  between L3 and L4. SR decreased significantly during the four 25-m lengths for the four groups ( $P < 0.05$ ) (Fig. 2A), corresponding to a decrease of 15.1% for G1, 11.9% for G2, 11.4% for G3, and 15.1% for G4 from L1 to L4. SL remained stable for G1 and G4, whereas it significantly decreased during the last two 25-m lengths for the two lower-speed groups ( $P < 0.05$ ) (Fig. 2B), corresponding to a decrease of 4% for G2 and 7.2% for G3.

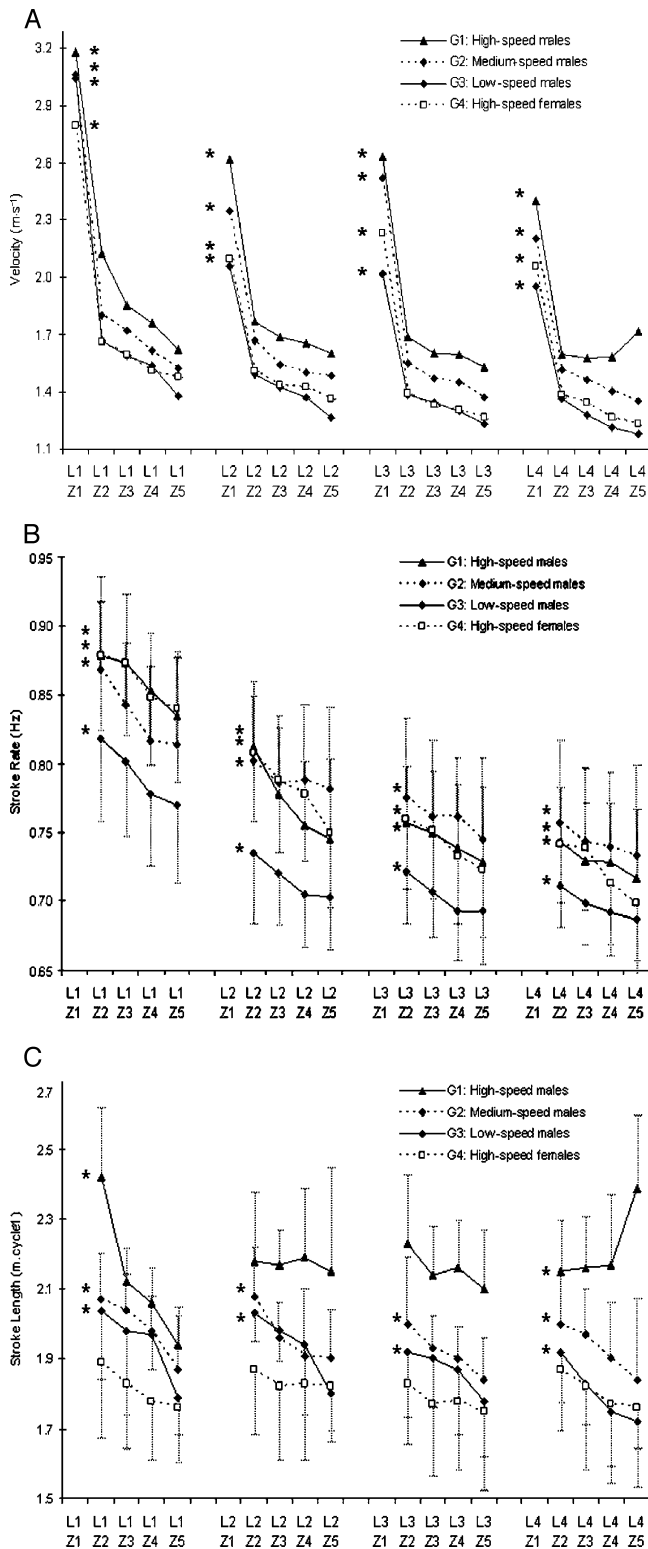
$V$  significantly decreased through the five zones of each length for the four groups ( $P < 0.05$ ), corresponding to a decrease from Z1 to Z5 of 50.3% at L1, 37.3% at L2, 42.4% at L3, and 36.8% at L4. This significant decrease in  $V$



**FIGURE 2—Relationship between the velocity and stroke rate (A) and stroke length (B) in the four groups. Regarding the decrease in velocity throughout the 100 m, the x-axis presents the highest- to the lowest-velocity data. \* Significant difference with the precedent length; \*\* significant difference with L1,  $P < 0.05$ .**

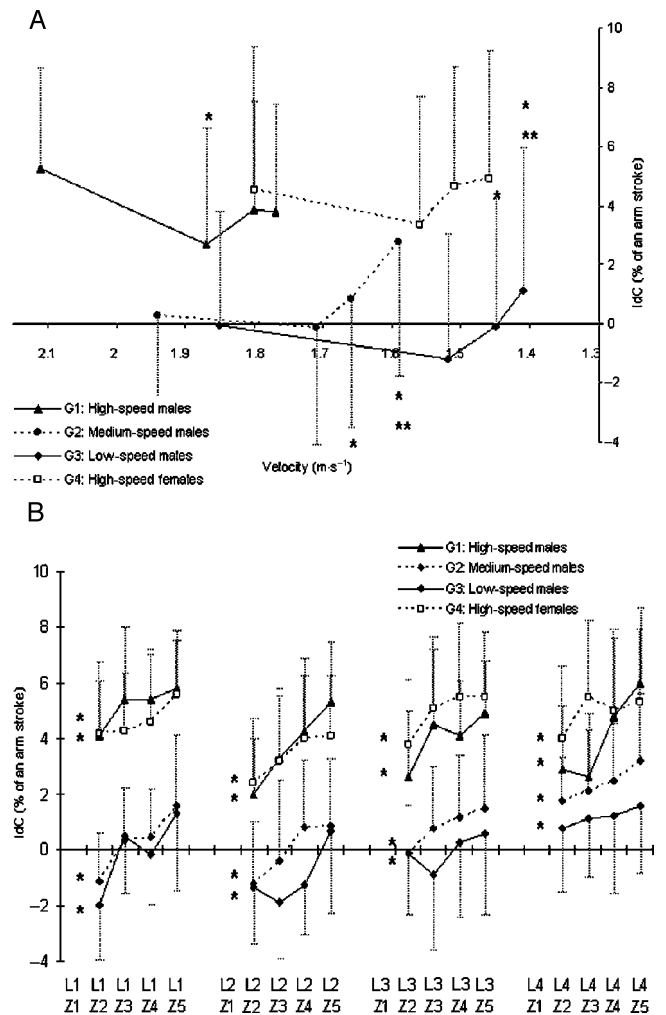
mainly occurred at Z1 ( $P < 0.05$ ) and was attributable to the push on the wall after the turn-out (Fig. 3A). G1 significantly increased  $V$  by 8.4% at Z5 of L4 ( $P < 0.05$ ), which was mostly attributable to the final sprint rather than to the underestimation of the Z5 duration. Indeed, only G1 increased  $V$  at Z5 of L4, whereas the overestimation of the  $V$  measurement concerned the four groups. SR significantly decreased through the four zones of each length for the four groups ( $P < 0.05$ ) (Fig. 3B). G1 significantly decreased SL through the four zones of L1 and significantly increased it by 10.1% at Z5 of L4 for the final sprint ( $P < 0.05$ ) (Fig. 3C). G2 and G3 significantly decreased SL by 8.6 and 10.3%, respectively, from Z2 to Z5 in all lengths ( $P < 0.05$ ) (Fig. 3C). G4 had a constant SL through the four zones of each length (Fig. 3C).

**IdC.** IdC was not significantly different between the elite males and females of, respectively, G1 and G4. It was, however, significantly different between G1, G2, and G3



**FIGURE 3—** *A*, Relationship between the velocity ( $V$ ) and the five zones of the four lengths. L, length; Z, zone; L1Z1, length 1–zone 1. \* Significant difference of  $V$  throughout the five 5-m zones,  $P < 0.05$ . *B*, Relationship between the stroke rate (SR) and the four zones of the four lengths. \* Significant difference of SR throughout the four 5-m zones,  $P < 0.05$ . *C*, Relationship between the stroke length (SL) and the four zones of the four lengths. \* Significant difference of SL throughout the four 5-m zones,  $P < 0.05$ .

for the whole 100 m and for each 5-m length ( $P < 0.05$ ). The high-speed swimmers swam in superposition coordination, whereas G2 and G3 swam in opposition coordination (Fig. 4A). For the whole population, IdC was significantly different between L1 and L2, L2 and L3–L4, and L3 and L4 ( $P < 0.05$ ). Nevertheless, these changes were significantly different in high- and low-speed male swimmers and between males and females ( $P < 0.05$ ). The high-speed males (G1) significantly decreased IdC between L1 and L2 and stabilized it from L3 to L4 ( $P < 0.05$ ) (Fig. 4A). Conversely, G2 and G3 maintained IdC between L1 and L3 and significantly increased it at L4 ( $P < 0.05$ ), so that they reached superposition coordination at this length. The high-speed females (G4) did not show significant IdC variation during the four 25-m lengths



**FIGURE 4—** *A*, Relationship between the index of coordination (IdC) and velocity in the four groups. Regarding the decrease in velocity throughout the 100 m, the x-axis presents the highest- to the lowest-velocity data. \* Significant difference with the precedent length; \*\* significant difference with L1,  $P < 0.05$ . *B*, Relationship between the IdC and the four zones of the four lengths. L, length; Z, zone; L1Z1, length 1–zone 1. \* Significant difference of IdC throughout the four 5-m zones,  $P < 0.05$ .

(Fig. 4A). IdC significantly increased from Z2 to Z5 in the four 25-m lengths for the four groups ( $P < 0.05$ ) (Fig. 4B).

**Arm-stroke phases.** The relative duration of the entry and catch phase (A) was significantly ( $P < 0.05$ ) shorter for the high-speed groups G1 and G4 than for G2 and G3, whereas the relative duration of the pull phase (B) was significantly longer ( $P < 0.05$ ) (Fig. 5). The relative duration of the push phase (C) was significantly longer for G1, G3, and G4 than for G2 ( $P < 0.05$ ) (Fig. 5). Thus, high-speed swimmers were characterized by a significantly longer relative duration of the propulsive phase (B + C) for the whole 100 m and for each 5-m length ( $P < 0.05$ ). G1 had a relative duration of the propulsive phase similar to that of G4 (respectively,  $54 \pm 3.8$  and  $54.4 \pm 4.5\%$ ), which was significantly higher ( $P < 0.05$ ) than for G2 and G3 (respectively,  $50.9 \pm 4.5$  and  $49.9 \pm 4.5\%$ ).

During L3 and L4, the high-speed swimmers (G1 and G4) and medium-speed males (G2) had a significantly shorter relative duration of the push phase than did the low-speed male swimmers (G3) ( $P < 0.05$ ); for G3, the relative duration of the push phase (C) in L3 was  $21.4 \pm 2.9\%$ , whereas for G1 it was  $20.9 \pm 2\%$ ; for G2,  $20.3 \pm 2.2\%$ ; and for G4,  $20.8 \pm 1.5\%$ . In L4, the relative duration of the push phase (C) for G3 was  $22.9 \pm 3.5\%$ , whereas for G1 it was  $21.5 \pm 1.8\%$ ; for G2  $21.4 \pm 2.2\%$ ; and for G4,  $21.6 \pm 1.9\%$ . The *post hoc* Tukey tests (group  $\times$  length) indicated that the relative duration of the push phase (C) of G3 increased significantly in L4 ( $P < 0.05$ ), which explained the significant differences in relative duration of the push phase among lengths for the whole population (Table 2).

Lastly, the *post hoc* Tukey test (group  $\times$  length) also indicated that for G1, the relative duration of the propulsive phase (B + C) was significantly longer in L1 ( $P < 0.05$ ), shorter in L2 ( $P < 0.05$ ), and then relatively stable in the other lengths. For G4, the relative duration of the propulsive

phase did not change significantly during the race. For G2 and G3, the relative duration of the propulsive phase significantly increased from L2 to L4 ( $P < 0.05$ ), explaining the increase in IdC.

**Leg kick.** All swimmers used a six-beat kick in each length and each zone, revealing stable leg kick.

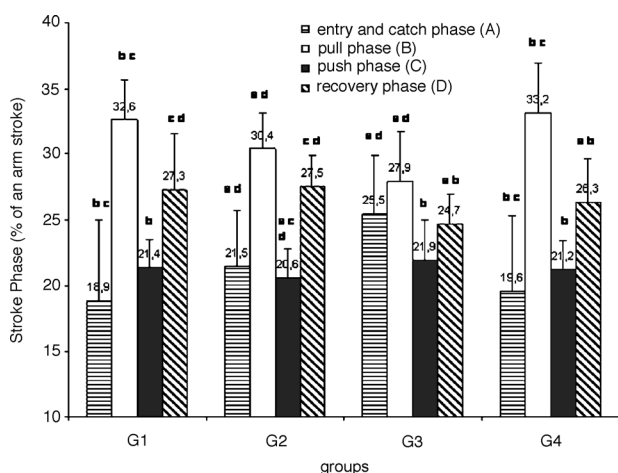
## DISCUSSION

The main findings of the present study indicate that during a 100-m front crawl, 1) high performance level was characterized by high and stable values of SL and IdC, and 2) the genders were differentiated by the greater SL of males compared with females.

### V, SR, SL

**Performance-level effect.** The performance-level differences were mainly the greater SR and SL of the high-speed males compared with the others and the capacity to keep these values high throughout the race. This confirmed the findings of previous studies comparing elite with nonexpert swimmers (1,5,8). Recent studies concerning elite swimmers (22,28) have confirmed that the high-speed swimmers (G1 and G4) had stable SL throughout the race and stable  $V$  in the last two lengths. On the contrary, the low-speed swimmers (G2 and G3) decreased  $V$  and SL throughout the 100 m, which could have been attributable to their incapacity to develop great power output and overcome high drag throughout the race (28). In high-level swimmers with disabilities, Daly et al. (8) have observed an increase in SL at the beginning of the 100 m and have indicated that the race was generally won or lost in lengths 2 and 4, suggesting that these lengths were determinant for the final results. They also indicate that SL explained most of the  $V$  changes during the second part of the 100 m. In the present study, the high-speed males and females used a similar strategy. They tended to improve SL in L2 and L4, whereas the low-speed swimmers decreased SL in L3 and L4.

Except at L1, the *intra*length comparisons confirm that the SL changes explain the  $V$  changes quite well throughout the race. At L1,  $V$  decreased from Z1 to Z5 by 50.3% because of the diving start (26). During the other lengths, fatigue would explain why  $V$  decreased from Z1 to Z5. Alberty et al. (1) have shown that for medium-level swimmers (best time on a 200 m at 78% of the world record), the decrease in  $V$  was attributable to decreases in SR and SL. Other studies have confirmed that when swimmers are exhausted, the decrease in  $V$  is related to a decrease in SL (7,8,12,30) and a decrease in SR, which is attributable to a 24% decrease in mechanical power output and, hence, slower hand velocity (28). Wakayoshi et al. (30) indicate that improving a swimmer's performance level would be reflected by a decrease in SR, an increase in SL, and a lower energy cost of swimming. In the present study, SL was the best discriminative factor of  $V$ . Indeed, the



**FIGURE 5—Differences in stroke phases in the four groups.** The propulsive phases (B and C) are solid; the nonpropulsive phases (A and D) are hatched; <sup>a</sup> Significant difference with G1; <sup>b</sup> significant difference with G2; <sup>c</sup> significant difference with G3; <sup>d</sup> significant difference with G4;  $P < 0.05$ .

medium- and low-speed groups decreased SL and  $V$  throughout the zones of each length, whereas SL remained constant for the high-speed swimmers (although SR decreased whatever the group between the zones of a length). The decrease in SL of the low-speed swimmers may also have been attributable to their poor technique during the turn-out, the effective push on the wall, and the correct timing to restart the stroke movement. Lastly, because the lower-speed swimmers took more time to complete the 100 m than did the high-speed male swimmers, they must swim a longer time in fatigued condition. Therefore, between Z4 and Z5 of L4,  $V$  and SL of G2 and G3 continued decreasing while the swimmers were performing the final sprint. Conversely,  $V$  and the SL of G1 slightly increased during the final sprint.

**Gender effect.** Males swam significantly faster than did females, although these high-speed females swam at the same velocity as the low-speed males. This gender effect was related to the male's greater SL, which, in turn, was related to the capacity of males to apply greater power output (25,29) and to overcome greater drag (29). Toussaint et al. (29) report that the greater height and body cross-sectional area of males explain the greater drag that they overcame, developing a greater SL than females. The relationships between anthropometric properties and drag, and thus SL, led to the identification of those anthropometric parameters associated with the greater SL. Grimston and Hay (10) have shown that axilla, hand and foot cross-sectional areas, leg frontal area, and leg and arm lengths were 89% correlated with SL, 41% with SR, and 17% with  $V$ . In our study, SL was 38.5% correlated with height, 36.6% with arm span, 50.7% with foot length, and 37.8% with hand length, suggesting that the greater SL of males was associated with their greater anthropometric values.

### IdC and Stroke Phases

**Performance-level effect.** High-speed swimmers were characterized by a long relative duration of the propulsive phase and, hence, high IdC values throughout the race. First, swimming fast is related to the motor control of swimmers who must solve the propulsion problem of maintaining a great mechanical power output (28), notably by adopting superposition coordination. Chollet et al. (4) and Lerda and Cardelli (14) have indicated that expert males have a higher IdC (i.e., superposition coordination) than do lower performers, who tend to use the arm catch-up and opposition coordination modes. Second, however, swimming fast and adopting superposition coordination are not only responses to organismic constraints (i.e., motor control); they are also the results of environmental constraints (i.e., drag, velocity) (24). The superposition coordination (high IdC) was not the determinant of high  $V$ , but it emerged from the high, active drag that swimmers must overcome to swim fast (13,27–29). Indeed, Chollet

et al. (4) and Seifert et al. (24) have demonstrated that, concomitant with the increase in drag with  $V^2$  (13,27–29), high-speed swimmers switch from catch-up to superposition over increasing paces from long-distance to sprint pace. Thus, in line with the findings on spatial–temporal parameters, which suggest that the maintenance of high  $V$  is related to high and stable SR (26) and SL (5,22), the high-speed swimmers (G1 and G4) adopted their preferential coordination (sprint pattern) and maintained a stable high IdC when *interlength* comparisons were considered. On the other hand, as regards the *intra*length comparisons, the high-speed males significantly increased their IdC from Z2 to Z5 of L2, L3, and L4 (22), showing their ability to increase the superposition of the arm actions after a glide time (because of the turn-out).

As did G1, G2 and G3 boosted their swim after the turn-out of each length by increasing their IdC. However, with regard to their lower  $V$  than G1, the drag to be overcome (i.e., environmental constraints, drag =  $KV^2$  (29)) was lower, so that G2 and G3 started with a smaller IdC (corresponding to opposition coordination). Moreover, because of their poorer technique and motor control (i.e., organismic constraints)—notably, to restart the stroke movement after the turn-out—G2 and G3 lacked the capacity to adopt a high IdC. Then, on the basis of the interpretation of Alberty et al. (1), who assessed the fatigue effect on IdC changes, it was postulated that fatigue onset led to an increase in IdC, indicating a switch to superposition coordination, in L4. Using an exhaustive exercise, Alberty et al. (1) have shown an increase in IdC from  $-6.55$  to  $-3.27\%$  in fatigue condition, which was related to a decrease in the relative duration of the nonpropulsive phase (catch and recovery phases) from 61.8 to 57.7% and a corresponding increase in the propulsive phase (pull and push phases) from 38.2 to 42.3%. Alberty et al. (1) have shown that the increase in the pull and push phases with fatigue could be attributable to the decrease in hand velocity, which was in accordance with the findings of Toussaint et al. (28). In the present study, the increase in IdC for G2 and G3 in the second part of the 100 m resulted from a longer relative duration of the hand spent in push phase. However, this motor change was ineffective because, unlike in the high-speed swimmers, SL continued to decrease throughout both lengths and zones, suggesting that the longer relative duration of the push phase of G2 and G3 was related to their smaller hand velocity. Satkunskiene et al. (20) note that swimmers with locomotor disabilities did not take advantage of the push phase. The propulsive force was related to an increase in the pull phase and a decrease in the entry + catch. Satkunskiene et al. (20) postulate that a long push was used more for body balance than for propulsion. Moreover, even though the relative duration of the push phase was longer for G2 and G3, a high average force is not as efficient as a high maximal peak force (6,21,27). In these latter studies, the authors show that the hand undergoes a constant change in direction



and alternating acceleration and deceleration during the underwater stroke and is unable to apply high, continuous forces. Thus, to have efficient coordination, swimmers must have effective direction, path, velocity, and hand angle (6,21).

**Gender effect.** Throughout the race, IdC values and variations were similar for the high-speed males and females. Despite similar arm coordination, however, the females could not swim at the same velocity as the high-speed males. In fact, to swim at the same velocity as the low-speed males, the high-speed females used higher SR and IdC (superposition coordination) than the males, who used opposition coordination. Because these females could not achieve greater SL, they adopted a different motor organization. Seifert et al. (23,24) have shown that at different race paces, males have a higher IdC than females. However, at a given velocity, females have a higher IdC than males (23,24). Toussaint and Beek (27) and Toussaint et al. (29) have shown that females developed smaller mechanical power output and overcame lower drag than did males, explaining their shorter SL. Females compensate shorter SL by changing their arm coordination and SR.

Lastly, the only difference between the high-speed males and females was in L1. Consecutive to the diving start, the higher  $V$  of G1 could have been attributable to their high mechanical power output and the high drag overcome to maintain high  $V$  during the rest of the length. This management led them to adopt a longer relative duration of the propulsive phase with high IdC, whereas G4 maintained a constant IdC throughout the lengths of the race.

**Leg kick.** The significant correlation between SL and foot length confirms that the leg kick contributes to the

entire propulsion by increasing SL (11) and maximal  $V$  by 10% (9). The leg kick also contributes indirectly to propulsion by organizing arm–leg coordination (9,19). The six-beat kick was used by all four groups throughout the entire 100 m, indicating that the change in interarm coordination (IdC) of each group was not related to the leg kick but, rather, to race management, fatigue, and/or performance level.

## CONCLUSION

High performance was characterized by the higher  $V$ , SR, SL, propulsive phase, and IdC values seen in the high-speed swimmers compared with the medium- and low-speed swimmers, and by the stability of these values throughout the race. Because of fatigue in L4, medium- and low-speed swimmers spent more time with the hand in push phase and changed to superposition coordination. However, these kinematic changes were ineffective as SL continued to decrease throughout the 100 m.

The gender effect was mainly related to the longer SL of the high-speed males because of the higher drag to overcome and to their higher anthropometric values, notably their greater arm span, height, and foot and arm length that influence propulsion. High-speed males and females had similar IdC; however, the high-speed males showed high IdC from the start of the race, which explains their decrease in IdC between L1 and L2.

The six-beat kick was used by all four groups throughout the entire 100 m, indicating that the change in interarm coordination (IdC) of each group was not related to the leg kick.

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