Kinematic parameters and stroke rate variability in elite female 200-m swimmers in the four swimming techniques: Athens 2004 Olympic semi-finalists and French National 2004 Championship semi-finalists

Philippe Hellard, Jeanne Dekerle, M. Avalos, N. Caudal, M. Knopp, Christophe Hausswirth

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Key words: Performance, swimming, variability, dynamic systems, stroking parameters

Authors: P. Hellard [ab]; J. Dekerle [c]; M. Avalos [d]; N. Caudal [a]; M. Knopp [a]; C. Hausswirth [e]
Affiliations: [a] Département d'Etudes et Recherches, Fédération Française de Natation, Paris, France
[b] Faculté des Sciences du Sport de Bordeaux 2, UPRES 498 - Laboratoire Vie Sportive, Tradition, Innovation et Intervention, France
[c] University of Brighton, Eastbourne, East Sussex, UK
[d] INSERM U875, Université Bordeaux 2, France
[e] Département des Sciences du Sport, INSEP, Paris, France

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Abstract:

OBJECTIVES: The purpose of this work was to study stroke rate variability in elite female swimmers (200-m events, all four techniques) by comparing semi-finalists of Athens 2004 Olympic Games (group O, n=64) and French National 2004 Championship semi-finalists (group N, n=64). **METHODS:** Swimming velocity (V), stroke rate (SR), stroke length (SL) and coefficient of variation of stroke rate (CV_{SR}) of the first and second 100 meters were determined (V1, V2; SR1, SR2; SL1, SL2; $CV_{SR}1$, $CV_{SR}2$) and differences between the two parts of the events were calculated (ΔV; ΔSR; ΔSL; and, ΔCV_{SR}). **RESULTS:** In group O, SR1, SR2, SL1, and SL2 were significantly higher ($P < 0.001$) and ΔV, ΔSR, ΔCV_{SR} were significantly lower ($P < 0.01$) than in group N. $CV_{SR}1$ and $CV_{SR}2$ were significantly lower for freestyle and backstroke races in group O than in group N ($P < 0.001$). **CONCLUSIONS:** Stroke rate variability appears to depend on an interaction between the biomechanical requisites of the task (techniques) and the level of practice.

Introduction

Analysis of performance, an important step in defining training programs, involves an evaluation of strategies used by elite athletes. To assess those used by elite swimmers, several groups of researchers have analyzed technical and kinematic parameters during international competitions to study their relationship with performance.[1][2][3][4][5][6][7][8][9][10] Likewise, in female 200-meter events, it has been shown that high performance is associated with long SL and/or high SR.[1][2][3][4][5][6][7][8][9][10] SL would depend on technical skill and is described as an index of motor efficiency,[3][4][5] [11][12] while SR would be more related to neuromotor and energetic capacities.[12][13] Changes in stroking parameters within a race has been interpreted as a strategy used by swimmers to deal with several factors such as the increasing fatigue, adversity, the optimization of the transition zones (starts and turns) .[4][5] [7][8] [11] [14][15] It is likely that these changes in stroking parameters have been shown to be dependent on the swim style,[1][2] [7] [9] and the level of expertise.[4][5] [7] [11] [16]

Chollet et al.[17][18] and Seifert et al.[19][20] recently applied the theory of dynamic systems to interpret changes in SL and SR. A dynamic systems perspective focuses on the capacity of biological systems to generate spatiotemporal patterns using complex subsystems characterized by a large number of degrees of freedom.[21] This theoretical model interprets locomotion as a self-organized phenomenon whose rhythmic pattern emerges from the interactions between the neuromuscular system and the environment.[22][23][24][25][26] Using this theory, Chollet and co-workers,[17][18] [19][20] hypothesized that due of their biomechanical requisites, each swim stroke tends toward stable forms of coordination (i.e. attractors). Measuring lag time between the propulsive phases, Seifert et al.[20] proposed that when an elite freestyle swimmer increases his velocity, the so-called catch-up coordination pattern (i.e. when the propulsive phase of one arm starts at the time the propulsive phase of the other arm finishes) observed at lower velocities moves into a superposition coordination (when the propulsive phases of the two arms overlap) to pass through a phase of opposition. The change from one mode of coordination to another depends on "control parameters”, that can be swimming velocity, stroke rate, or even stroke length.

All of these studies presented studied changes in the spatiotemporal parameters. But to our knowledge, no investigation has been conducted to examine the inter-cycle variability of these biomechanical parameters. This inter-cycle variability is known however to be an important indicator of performance level and motor skill.[22] [26][27] [28].

The purpose of this study was to compare the stroke length, stroke rate, and stroke rate variability observed in elite female swimmers participating in 200-meter events. Comparisons were made between the four swimming techniques and between swimmers (Athens 2004 Olympic Games and French National 2004 Championship semi-finalists). We hypothesized that stroke length, stroke rate, and stroke rate variability would depend on the four different techniques being performed and the level of performance.

Materials and methods

The 200-m event performances of the female semi-finalists of the Athens Olympic Games (n=64, average performance level = 97.15% of world record) and the female semi-finalists of the French National 2004 Championship (n=64, average performance level = 91.58% of world record) were recorded. The same video recording set up and data processing system (Figure 1) were used for both competitions.

Video recording

Four cameras (Panasonic NVDS11) were positioned perpendicular to the long axis of the pool, at 7.5m, 15m, 25m and 42.5m from the starting block. The camera signals were captured by a video mixer (Videonics MX1) and sent to a video timer (FOR.A VTG55) which inserted a chronometer (linked to the official chronometer) into the video image. The video image was then digitalized in real time for computer processing. The film of each race was analyzed with a dedicated software that calculated the time between camera points for each swimmer. To calculate stroke duration, the system included an eight-bit micro controller (PIC 16F84) triggered by the official chronometer and linked to the computer's data acquisition system. The time point of each arm entry was noted for each swimmer during the entire race (one observer per line). The durations of the strokes recorded for the female 200-m freestyle Olympic champion are presented in Figure 2.

Swim velocity

Swim velocity expressed in $m.s^{-1}$ (V) was recorded as the mean for the first 100 m (V1) and the second 100 m (V2), excluding the starting (SZ), finishing (FZ), and turning zones (TZ) (Figure 1).

Stroke rate and stroke length

SR was calculated for each cycle using the equation (SR=60/stroke duration) and expressed in strokes per minute ($s.min^{-1}$). SL was determined with the equation (SL=V/SR/60) and expressed in meters per stroke. Mean SR and mean SL were calculated using all values recorded for each 100 m, for each of the four pure swim zones (excluding the starting, finish, and turning zones) and for the first 100 m (SR1, SL1) and second 100 m (SR2, SL2).

Evaluation of the instantaneous stroke rate measurement system

Eight observer-trainers with a scientific background evaluated stroking parameters cycle by cycle. After each training phase, each observer interpreted the video recording of one race of the same swimmer 30 times in order to quantify intra-observer error as described by Bland and Altman [29]. Inter-observer error was determined with the same methodology, two different observers interpreting the video recordings of 30 different swimmers. The 95% interval of confidence was determined to assess observer bias (same observer recording higher or lower results for the same subject or one observer producing higher or lower results than another).

Coefficient of variation of stroke rate

For each event, the coefficient of variation of stroke rate, defined as the standard deviation divided by the mean, stroke by stroke, was determined for the first ($CV_{SR}1$) and the second 100 meters ($CV_{SR}2$). The variation between $CV_{SR}1$ and $CV_{SR}2$ ($\Delta CV_{SR} = CV_{SR}1 - CV_{SR}2$) was also calculated. 73 ± 21 strokes in butterfly and breaststroke and 217 ± 31 strokes in backstroke and freestyle were analyzed.

Statistical analysis

Values are expressed as mean ± standard deviation. The Shapiro Wilk test was used to check the hypothesis of normal distribution ($P < 0.05$). Two-way analysis of variance (ANOVA) [four strokes (butterfly, breaststroke, backstroke, freestyle) x performance level (Olympic and National)] was used to search for independent variables. The student Newman-Keuls post-hoc test was then applied to search for significant effects. Data analysis was performed with Matlab 200, 6.0 Optimization Toolbox (Mathwords, eds.) The threshold for significance was set at the 0.05 level of confidence.

Results

Results of the comparisons between the Olympic-level (group O) and National-level (group N) swimmers are presented in Table 1. Comparisons between the four swimming techniques are presented in Table 2 and 3.

Table 1. Performance parameters for group O (Olympic semi-finalists) and group N (French national championship semi-finalist).

Parameter		Butterfly		Backstroke		Breaststroke		Freestyle	
Performance (s)	**O**	130.52 (1.33)		132.42 (1.73)		148.07 (1.97)		119.48 (0.76)	
	N	139.74 (2.57)	***	139.94 (4.01)	***	158.03 (2.66)	***	127.34 (3.17)	***
V1($m.s^{-1}$)	**O**	1.54 (0.02)		1.48 (0.01)		1.33 (0.02)		1.64 (0.02)	
	N	1.45 (0.03)	***	1.41 (0.03)	***	1.24 (0.02)	***	1.55 (0.02)	***
V2 ($m.s^{-1}$)	**O**	1.44 (0.02)		1.42 (0.03)		1.27 (0.02)		1.67 (0.08)	
	N	1.33 (0.03)	***	1.33 (0.04)	***	1.18 (0.02)	***	1.50 (0.03)	***
ΔV ($m.s^{-1}$)	**O**	0.10 (0.02)		0.05 (0.03)		0.05 (0.03)		-0.02 (0.11)	
	N	0.11 (0.03)		0.06 (0.02)		0.06 (0.02)		0.06 (0.02)	
SR1 ($c.min^{-1}$)	**O**	50.13 (4.09)		40.98 (2.84)		36.59 (4.91)		44.32 (4.01)	
	N	48.51 (3.19)		38.74 (2.87)	*	35.76 (3.15)		44.33 (2.94)	
SR2 ($c.min^{-1}$)	**O**	49.32 (3.99)		40.68 (3.22)		37.94 (4.21)		44.05 (3.58)	
	N	47.33 (3.04)		37.41 (2.61)	**	36.79 (3.71)		43.74 (2.47)	
ΔSR ($c.min^{-1}$)	**O**	0.81 (1.33)		0.32 (1.33)		-1.34 (1.79)		0.26 (1.08)	
	N	1.17 (1.51)		1.33 (1.58)		-1.02 (2.22)		0.68 (1.43)	
SL1 (m)	**O**	1.85 (0.15)		2.18 (0.15)		2.18 (0.26)		2.26 (0.19)	
	N	1.79 (0.11)		2.20 (0.15)		2.11 (0.18)		2.11 (0.15)	*
SL2 (m)	**O**	1.76 (0.14)		2.11 (0.18)		2.01 (0.24)		2.18 (0.17)	
	N	1.69 (0.09)		2.14 (0.12)		1.94 (0.17)		2.06 (0.13)	*
ΔSL (m)	**O**	0.09 (0.04)		7.03 (7.51)		0.18 (0.07)		0.08 (0.05)	
	N	0.11 (0.04)		5.09 (8.27)		0.17 (0.2)		0.05 (0.06)	
$CV_{SR}1$ (%)	**O**	4.77 (0.78)		4.61 (1.26)		6.09 (1.18)		4.63 (1.43)	
	N	4.84 (1.14)		7.20 (1.54)	***	6.69 (2.16)		6.92 (1.65)	***
$CV_{SR}2$ (%)	**O**	3.99 (0.85)		3.09 (0.70)		6.43 (1.85)		3.96 (0.97)	
	N	4.27 (1.75)		5.73 (1.49)	***	5.57 (1.35)		6.26 (1.53)	***
ΔCV_{SR} (%)	**O**	0.78 (0.85)		1.55 (1.36)		-0.34 (1.98)		0.67 (1.53)	
	N	0.56 (1.12)		1.47 (1.07)		1.11 (2.41)		0.66 (0.97)	

(V1, V2, $m.s^{-1}$; SR1, SR2, $s.mn^{-1}$; SL1, SL2, m; $CV_{SR}1$, $CV_{SR}2$, %) swim velocity, stroke rate, stroke length, coefficient of variation for the first and the second 100 m respectively. Significantly different between group O (Olympic semi-finalists) and group N (French national championship semi-finalist) ($P < 0.05$), * Significantly different between group O and group N ($P < 0.05$), ** Significantly different between group O and group N ($P < 0.01$), *** Significantly different between group O and group N ($P < 0.001$).

Table 2. Performance parameters for the four swimming techniques, butterfly, backstroke, breaststroke, freestyle.

Parameter	Butterfly	Backstroke	Breaststroke	Freestyle
Performance (s)	134.82 (5.22) $^{\Theta\dagger\Delta}$	136.07 (4.23) $^{*\dagger\Delta}$	153.53 (6.21) $^{*\Theta\Delta}$	122.56 (3.55) $^{*\Theta\dagger}$
V1(m.s^{-1})	1.50 (0.05) $^{\Theta\dagger\Delta}$	1.44 (0.04) $^{*\dagger\Delta}$	1.28 (0.04) $^{*\Theta\Delta}$	1.63 (0.02) $^{*\Theta\dagger}$
V2 (m.s^{-1})	1.39 (0.06) $^{\dagger\Delta}$	1.38 (0.05) $^{\dagger\Delta}$	1.22 (0.05) $^{*\Theta\Delta}$	1.61 (0.09) $^{*\Theta\dagger}$
ΔV (m.s^{-1})	0.11 (0.02) $^{\Theta\dagger\Delta}$	0.06 (0.02) $^{\dagger\Delta}$	0.06 (0.02) $^{*\Delta}$	0.01 (0.08) $^{*\Theta\dagger}$
SR1 (c.min^{-1})	49.37 (3.73) $^{\Theta\dagger\Delta}$	39.91 (3.03) $^{*\Delta}$	35.98 (3.89) $^{*\Delta}$	44.72 (3.69) $^{*\Theta\dagger}$
SR2 (c.min^{-1})	48.39 (3.66) $^{\Theta\dagger\Delta}$	39.09 (3.33) $^{*\Delta}$	37.24 (3.88) $^{*\Theta\Delta}$	43.94 (3.08) $^{*\Theta\dagger}$
ΔSR (c.min^{-1})	0.98 (1.41) †	0.81 (1.52) †	-1.25 (1.82) $^{*\Theta\Delta}$	0.78 (1.43) †
SL1 (m)	1.83 (0.13) $^{\Theta\dagger\Delta}$	2.19 (0.14) *	2.15 (0.21) *	2.21 (0.17) *
SL2 (m)	1.73 (0.12) $^{\Theta\dagger\Delta}$	2.13 (0.15) *†	1.98 (0.21) $^{*\Theta\Delta}$	2.15 (0.15) *†
ΔSL (m)	0.09 (0.04) †	0.06 (0.08) †	0.17 (0.09) $^{*\Theta\Delta}$	0.06 (0.07) †

(V1, V2, m.s^{-1}; SR1, SR2, c.mn^{-1}; SL1, SL2, m; $CV_{SR}1$, $CV_{SR}2$, %) swim velocity, stroke rate, stroke length, coefficient of variation for the four swimming techniques, butterfly, backstroke, breaststroke, freestyle respectively. * Significantly different from butterfly, $^{\Theta}$ significantly different from backstroke, † significantly different from breaststroke, $^{\Delta}$ significantly different from freestyle, all for $P < 0.001$.

Swimming velocity

There was a significant difference between the two groups of swimmers (ANOVA: variable × Level of performance, Table 1) and between the four techniques (ANOVA: variable × swimming technique, Table 2), regarding swimming velocity (P<0.001) and variation in the swimming velocity between the first and the second 100 meter (P<0.001). ΔV butterfly was significantly greater than ΔV backstroke, ΔV breaststroke and ΔV freestyle. ΔV freestyle was significantly lower than ΔV butterfly, ΔV breaststroke, and ΔV backstroke (P<0.001).

Stroke length

Level of performance (ANOVA: variable × Level of performance, Table 1) and type of swimming techniques (ANOVA: variable × swimming technique, Table 2) were found to significantly affect SL1, SL2, and ΔSL. SL1 was shorter for butterfly than for backstroke, breaststroke, and freestyle (P < 0.001). SL2 was longer for backstroke and freestyle than for breaststroke. Regarding performance level, SL1 and SL2 were greater in group O for all four strokes (2.12 ± 0.24; 2.03 ± 0.24 *vs*. 2.05 ± 0.21; 1.96 ± 0.21; P < 0.05). SL1 and SL2 were greater in group O for freestyle (P < 0.05). ΔSL was greater in group O for breaststroke than for the three other strokes (P < 0.001).

Stroke rate

Level of performance (ANOVA: variable × Level of performance, Table 1) and type of swimming technique (ANOVA: variable × swimming technique, Table 2) were found to significantly affect SR1, SR2, and ΔSR. SR1 was greater for butterfly than for backstroke, breaststroke, and freestyle (P < 0.001) and greater for freestyle than for backstroke and breaststroke (P < 0.001). For SR2, the values declined in the following order: butterfly, freestyle, breaststroke, backstroke, P < 0.001). ΔSR was lower for breaststroke than butterfly, backstroke and freestyle (P < 0.001). Regarding performance level, group O exhibited higher SR1 and SR2 for all four strokes (43.71 ± 6.27; 43.11 ± 5.61 *vs*. 41.68 ± 5.76; 41.22 ± 5.29, P < 0.001) and lower ΔSR (0.01 ± 1.51 *vs*. 0.54 ± 1.92, P < 0.05). SR1 and SR2 were higher in group O for backstroke (P < 0.05).

Stroke rate variability

Type of swimming technique (ANOVA: variable × swimming technique, Table 3), level of performance (ANOVA: variable × Level of performance, Table 1), and the interaction of these two factors (ANOVA: variable × Level of performance × swimming technique) had a significant effect on $CV_{SR}1$, $CV_{SR}2$, and Δ CV_{SR} (P < 0.01). $CV_{SR}1$ for butterfly was significantly lower than $CV_{SR}1$ for backstroke (P < 0.05) and breaststroke (P <

0.01). $CV_{SR}2$ for breaststroke was significantly greater than $CV_{SR}2$ for backstroke ($P < 0.05$) and butterfly ($P < 0.05$). Δ CV_{SR} for backstroke was significantly greater than ΔCV_{SR} for breaststroke ($P < 0.05$). Regarding level of performance, $CV_{SR}1$ and $CV_{SR}2$ were lower for all four strokes in group O (5.03 ± 1.31 *vs*. 6.41 ± 1.87 and 4.37 ± 1.68 *vs*. 5.46 ± 1.66), and specifically for backstroke and freestyle ($P < 0.001$; Table 1). Mean inter-observer error was 7.4% (95% interval of confidence: 7.1-7.8%).

Table 3. Coefficients of variation for the four swimming techniques, butterfly, backstroke, breaststroke, freestyle.

	Butterfly	**Backstroke**	**Breaststroke**	**Freestyle**
$CV_{SR}1$ (%)	4.8 (0.9) $^{\Theta, \dagger}$	5.9 (1.9)	6.4 (1.7)	5.8 (1.9)
$CV_{SR}2$ (%)	4.1 (1.4) †	4.4 (1.7) ††	6.0 (1.6)	5.1 (1.7)
ΔCV_{SR} (%)	0.7 (0.9)	1.5 (1.2) †	0.4 (2.3)	0.7 (1.2)

$^{\Theta}$ Significantly different from backstroke, † Significantly different from breaststroke. † for $P<0.05$ and †† for $P<0.01$.

Discussion

The purpose of this study was to compare kinematic parameters and CV_{SR} in female 200-m swim events. The main findings were: (i) SL and SR were different for the four techniques. SL was shorter for butterfly and longer for backstroke and freestyle; (ii) SL and SR were different among swimmers with different performance levels. The Olympic-level swimmers exhibited faster backstrokes and longer freestyle strokes; (iii) CV_{SR} depended on techniques and performance level. Olympic-level swimmers exhibited less CV_{SR}.

Stroke length and stroke rate: Between-stroke comparisons

SL were longer for alternating arm strokes compared with simultaneous arm strokes, as previously reported.[1][2][3][4] [6][7] [9] For alternating strokes, one arm is in the propulsion phase while the other is in the recovery phase.[11] [19][20] These alternate actions, together with a profiled body position, ensure a continuous motor effect at low energy cost.[13][14] Moreover, body roll, which allows the arms to go further ahead in the beginning of the underwater action, as well as a longer upsweep when finishing the stroke enables a longer SL in freestyle and backstroke.[14] [30][31] Although most studies indicate that SL is greater for backstroke, then in declining order for freestyle, butterfly, and breaststroke,[3][4] [6][7] our results and those published recently by others,[1][2] [9] show that the decreasing order is freestyle, backstroke, breaststroke, and butterfly. Since the early work of Craig and Pendergast,[6] the increase in SL of 200-m female swimmers has been greater in freestyle and breaststroke than in butterfly probably due to the possibilities of exploiting the gliding phases in breaststroke and freestyle swimming.[18][19][20]

The changes observed in SR over the last 25 years,[1][2][3][4] [7] [9] illustrate a similar trend. Since 1979, small SR changes for 200-m butterfly and backstroke races have been recorded (≈ 50 $s.min^{-1}$ for butterfly and 42 $s.min^{-1}$ for backstroke) while SR decreased by more than 10 $s.min^{-1}$ for breaststroke and freestyle races. Thus it appears that for optimal performance in backstroke and butterfly races, SR must rise above a minimal threshold. Unlike freestyle and breaststroke, the butterfly stroke induces biomechanical constraints hindering full utilization of the gliding phase. Indeed, in breaststroke, the center of gravity is lower during the phases when the arms move forward, enter the water, and push downward. [32] Furthermore, major intra-stroke variations in the velocity of the center of mass are correlated with less efficient swimming.[33] Swimmers thus adapt their strategy to limit the lost of velocity during the non-propulsive phases by better coupling the propulsive actions of their propulsive segments.[17] [32] With the backstroke however, the propulsive action is discontinuous because of the anatomic configuration of the shoulder joint at the beginning of the pull phase and the roll of the body at the end of the push phase as the arm leaves the water.[31] Thus the best backstroke swimmers adapt their strategy by moving their arm out of the water more rapidly,[30] which probably implies a more rapid SR.

Stroke length and stroke rate: Between-group comparisons

The Olympic swimmers had longer SL than the National-level swimmers, confirming data reported by others.[6][7][8] [10] SL has been interpreted as a index of high propulsive efficiency,[12][13] resulting from greater propulsive force generated by the arms and legs (higher peak force),[18] associated with more effective coordination patterns between propulsive and gliding phases.[11] [17][18] [20]

Looking at all four techniques, the Olympic swimmers were also characterized by higher SR, which persisted throughout the race. These results are in line with data from many studies which have identified SR as a factor of performance.[1][2][3] [9] [10] The capacity to maintain a high SR until the end of the race is associated with muscular power,[13] neuromotor control and muscular endurance.[16] Like others,[1][3] we found that the highest backstroke rate was observed in the Olympic swimmers, probably related to coordination patterns characterized by more rapid arm movement out of water as has been observed in expert swimmers.[30]

Nevertheless, some of our results are in disagreement with the literature. For the 200-m breaststroke races, we did not find any difference between group O and group N for SR or stroke length. This is in contradiction with data reported by others.[2][3] [7] [9][10] The discordance could be related to the study populations since it is known that swimming velocity, SR, and SL are not linearly related.[6] [13] [16] This would explain why differences observed between swimmers with different performance levels (for example Olympic series swimmers versus finalists) are no longer observed when comparing populations with very similar performance levels (for example semi-finalists and finalists).

Variability in stroke frequency: Between-group and between-stroke comparisons

Our original approach was to analyze CV_{SR} in a population of elite Olympic- and National-level swimmers. The values obtained in this population can serve as a reference. Statistically, all of the significant differences in the coefficients of variation were greater than the interval of confidence of the measurement method, demonstrating the absence of a methodological bias in the statistical interpretation.[29] The greater variability in the breaststroke rate could be explained by changes in the coordination patterns often observed in this stroke.[19][20] The breaststroke is characterized by a greater time lag between arm and leg movements and a longer glide time which enables the swimmers to shorten or lengthen transition phases between arm and leg movements.[18] The underwater recovery movement of the arms and legs creates drag at high swim velocity.[18] [34] The propulsive forces of the limbs are also greater than in the other three strokes.[18] Thus logically, coordination patterns could vary during the same race. At the beginning of the race, the swimmer probably uses the most economical strategy, optimizing the glide phase placed after the leg stroke augmenting its stroke length.[13] Inversely, at the end of the race, the swimmer favors propulsion by increasing SR. This would induce greater CV_{SR} for breaststroke than for the other three strokes. Inversely, in butterfly, the coordination pattern would remain relatively stable for different swimming velocities.[17] This could explain the lower CV_{SR} compared with the other strokes. In butterfly, swimmers have to achieve a precise synchronization between the respiration phase and three (one-arm and two-leg) or two (one-arm and one-leg) movements, each movement being composed of an ascending phase and a descending phase.[14] [17] This would leave less room for modifying coordination patterns. The variabilities observed for backstroke and freestyle were significantly greater than in butterfly, suggesting that, as is observed in running and walking, a major part of the variability depends on movement asymmetry,[26] and the requirement to successively redirect the center of mass forward after each lateral movement of the limbs.[23][24] The

Olympic swimmers exhibited significantly less CV_{SR} in freestyle and breaststroke races, providing confirmation of the lesser movement variability in the most skilled athletes performing high-velocity tasks strongly influenced by movement asymmetry. [22] [26][27][28]

Lesser CV_{SR} was a characteristic feature observed in the Olympic-level swimmers. Sidney et al.[15] also demonstrated that the capacity to maintain a constant stroke throughout the race is a characteristic skill in 100-m and 200-m swims. Several authors found that movement variability is an important indicator of performance level and motor skill.[22] [26][27] [35] In runners, it has also been demonstrated,[36] that stride rate variability and stride rate are related to energy cost. For runners, stride variability has been found to be associated with increased velocity.[36][37][38] In the same way, we found that at higher velocities, Olympic-level swimmers exhibited less CV_{SR} compared with National-level swimmers.

Tentative of interpretation using the theory of the dynamic systems

In the dynamic systems theory, movement is considered as an emerging property which results from the interaction between the self-organization capacity of the neuromusculoskeletal system, represented in our study by individual skill or performance level, and the task requisites, represented in our study by the four swim strokes.[21] [26][27] [39] Using the dynamic systems theory to better understand the results of the present study, the differences in the variability of the swimmers' motor patterns could be interpreted as an effect of the stroke requisites which set specific limits for self-organization. The lower variability observed in the Olympic swimmers could thus be interpreted as stability and optimal efficiency obtained by system coupling.[22][23][24][25][26] [39]

Conclusion

SR, SL, and CV_{SR} are dependent on the interaction between the biomechanical requisites of the task (swimming techniques) and individual skill. Female Olympic swimmers are characterized by faster backstroke SR, longer freestyle SL, and less CV_{SR}. These findings open the perspective of experimental analysis of stroke variability by imposing fixed SR and SL. This would enable a better understanding of the effects of voluntary modulation of SR or amplitude to adapt performance to competitors or fatigue during the course of the race.

Captions

Figure 1. Video recording set up (SZ, start zone; TZ, turn zone; FZ, finish zone; T1, T2, T3 et T4 ; pure swim times between camera points).

Figure 2. Stroke rate modulations observed in the Olympic champion during the female 200-m freestyle Olympic final.

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