Kinematic measures 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.

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Abstract

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). Since swimming **speed** (V) is the product of stroke rate (SR) and stroke length (SL), these three variables and the 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; ΔCV_{SR}). When the results for the four 200m events were analysed together, SR1, SR2, SL1, and SL2 **were higher** ($\alpha = 0.05$, $p < 0.001$) and ΔV, ΔSR, ΔCV_{SR} **were lower** ($p < 0.01$) in group O than in group N. The **Olympic-standard** swimmers exhibited faster backstrokes and longer freestyle strokes ($p < 0.05$). $CV_{SR}1$ and $CV_{SR}2$ were lower for freestyle and backstroke races in group O than in group N ($p < 0.001$). Stroke rate variability appears to depend on an interaction between the biomechanical requisites of the task (techniques) and **the standard** of practice.

Key words: Performance, swimming, variability, dynamic systems, stroking **characteristics**

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 analysed technical and kinematic **characteristics** during international competitions **to investigate** their relationship with performance (East, 1970; Craig and Pendergast, 1979; Chengalur and Brown, 1992; Chollet *et al.*, 1997; Chatard *et al.*, 2001a; Chatard *et al.*, 2001b; Thomson *et al.*, 2000; Girold *et al.*, 2001). Likewise, in female 200-meter events, it has been shown that high performance is associated with long **stroke length** and/or high **stroke rate** (Craig and Pendergast, 1979; Craig et al., 1985; Chengalur and Brown, 1992; Chollet et al., 1996; Chollet *et al.*, 1997; Chatard *et al.*, 2001a; Chatard *et al.*, 2001b; Thomson *et al.*, 2000; Girold *et al.*, 2001). **Stroke length depends** on technical skill and is described as an index of motor **effectiveness** (Chengalur and Brown, 1992; Chollet *et al.*, 1996; Chollet *et al.*, 1997; Seiffert et *al.*, 2005) while **stroke rate** would be more related to neuromotor and energetic **capabilities** (Wakayoshi et al., 1993; Wakayoshi et al., 1995). Changes in stroking **characteristics** within a race **have** been interpreted as a strategy used by swimmers to deal with several factors such as increasing fatigue, adversity **and optimization of transition zones** (starts and turns) (East, 1970; Craig *et al.*, 1985; Costill *et al.*, 1992; Chollet *et al.*, 1996; Chollet *et al.*, 1997; Sidney *et al.*, 1999; Girold *et al.*, 2001; Seiffert *et al.*, 2005). It is likely that these changes in stroking **characteristics are dependent on swimming style** (Craig *et al.*, 1985; Chatard *et al.*, 2001a; Chatard *et al.*, 2001b; Girold *et al.*, 2001) **and the standard of the swimmer** (Craig *et al.*, 1985; Keskinen and Komi, 1993; Chollet *et al.*, 1996; Chollet *et al.*, 1997; Seiffert *et al.*, 2005). Observing women's 200-m backstroke events, Craig *et al.* (1985) reported that a large decrement in **stroke length** exhibited by the swimmers was compensated for by increasing **stroke rate**. Conversely, a continuous decline in **stroke length** and **stroke rate** was observed in **the other**

three events. During the Sidney 2000 Olympic Games, **stroke rate** in female semi-finalists in the 200-m freestyle and breastroke events declined during the first 50 m then increased during the last 50 m, associated with a continuous decline in **stroke length** during the last three 50-m stretches (Chatard *et al*., 2001a; Chatard *et al*., 2001b; Girold *et al*., 2001). Although adaptation of stroking **characteristics** to race conditions has been interpreted as a factor of expertise (East, 1970; Craig *et al*., 1985; Costill *et al*., 1992; Sidney *et al*., 1999; Seiffert *et al*., 2005), several authors have nevertheless postulated that higher performance swimmers consistently exhibit more stable **stroke length** and **stroke rate** (Chollet *et al*., 1997; Sidney *et al*., 1999; Seiffert *et al*., 2005).

Chollet *et al*. (2001, 2004) and Seifert et al. (2004a, b) recently applied the theory of dynamic systems to interpret changes in **stroke length** and **stroke rate**. A dynamic systems perspective focuses on the **ability** of biological systems to generate spatiotemporal patterns using complex subsystems characterized by a large number of degrees of freedom (Schöner and Kelso, 1988). This theoretical model interprets locomotion as a self-organized phenomenon whose rhythmic pattern emerges from the interactions between the neuromuscular system and the environment (Newell and Corcos, 1993; Donelan *et al*., 2001; Masani *et al*., 2002; Danion *et al*., 2003; Donelan *et al*., 2004). Using this theory, Chollet and co-workers (Chollet et Boulesteix, 2001; Chollet *et al*., 2004; Seiffert *et al*., 2004a, b) hypothesized that due **to** 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*. (2004b) proposed that when an elite freestyle swimmer increases his **speed**, 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 **speeds**, 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 **characteristics**" that can be swimming **speed**, stroke rate or even stroke length.

All of these studies presented analysed changes **in these** spatiotemporal **characteristics**. But to our knowledge, no investigation has been conducted to examine the inter-cycle variability of these biomechanical **factors**. This inter-cycle variability is known, however, to be an important indicator of performance **standard** and motor skill (Newell and Corcos, 1993; **Slawinski *et al.*, 2001**; Danion *et al*., 2003; Davids *et al*., 2003; Yoshino *et al*., 2004). Furthermore, any given swim stroke performed in **competition requires**, like competitive walking (Brisswalter *et al*., 1998), a specific motor response to achieve proper execution in compliance with the **sport's rules**.

The purpose of this observational and exploratory study was to compare the stroke length, stroke rate, and stroke rate variability in elite female swimmers participating in 200-meter events. Comparisons were made between strokes and between expert swimmers of different **standard of performance** (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 types of stroke** and **standard** of performance.

Materials and methods

Experiments conducted by the authors were funded by the French Swimming Federation and the International Amateur Swimming Federation who granted permission to use the data for research purposes and publication.

The 200-m event performances of the female semi-finalists of the Athens Olympic Games n=64, **mean standard** = 97.15% of world record, **mean stature** (171 ± 6; 175 ± 6; 171 ± 6; 173 ± 6 cm) for butterfly, backstroke, breastroke, and freestyle respectively, mean age (23 ± 4; 21 ± 2; 22 ± 3; 23 ± 5 yrs respectively), and the female semi-finalists of the French National

2004 Championship, n=64, **mean standard** = 91.58% of world record, mean **stature** (172 ± 4; 172 ± 6; 170 ± 4; 171 ± 6 cm) for butterfly, backstroke, breastroke, and freestyle respectively, mean age (21 ± 2; 20 ± 4; 19 ± 3; 20 ± 2 yrs respectively) were recorded. The same video recording set up and data processing system (Figure 1) were used for both competitions.

Video recording

Four transversal cameras equipped with a wide angle to obtain a wider field of vision were positioned perpendicular to the long axis of the pool, at 7.5 m, **15.0 m, 25.0 m** and 42.5 m from the starting block. **The cameras** were linked to a Videonics MX1digital video mixer. This digital video mixer accepts input from four video camera sources on the same screen display (Hewlett Packard 1024x768), **and allows switching of one camera image to another**. Adobe Première 6.0 was used to convert the analogic video signal into a digital video signal (AVI) and reframe at 50 images per second. The film of each race was analysed with dedicated software (Actriss, Brest, France) that calculated the time between camera points for each swimmer. The developed software includes all the typical options such as drawing references and collecting time data **and includes** all data in the database. The files are replayed in slow-motion, so the film can be repositioned image by image with the zoom. The software uses the appropriate **characteristics** (identification of the water lines, identification of the swimmers, determination of intermediate times from the oblique transversal lines generated in superposition with the analogue video signal produced by each camera) to align each image with the most distant water line. To calculate stroke duration, the system included an eight-bit micro controller (PIC 16F84) triggered by the official **chronometer linked** to the computer's data acquisition system. Clicking on the water line at different moments characteristic of the swimming stroke generates the instantaneous stroke rate. The external chronometer is linked to the official chronometer added after the mixer using a transparent filter **that** does not affect image resolution. 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 speed

Swim **speed** 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

Stroke rate was calculated for each cycle using the equation (SR=60/stroke duration) and expressed in strokes per minute ($s.min^{-1}$). **Stroke length** was determined with the equation (SL=V/SR/60) and expressed in meters per stroke. Mean **stroke rate** and mean **stroke length** 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).

Stroke rate measurement system training process

Eight coaches with a scientific background were trained using video recordings obtained during the preceding competition. With the help of scientific experts, for each of the four swimming techniques, the characteristic moments of the onset of each swim stroke were identified. Each operator then analysed the same video recording 30 times searching for the same values as noted by the scientific expert evaluator.

Evaluation of the instantaneous stroke rate measurement system

After each training phase, **to quantify reproducibility** of the instantaneous stroke rate measurement system, each observer interpreted the video recording of one race of the same swimmer 30 times. The **within-participant** standard deviation or the standard error of measurement as described by Bland and Altman (1986), $s_w = \sqrt{\frac{1}{N}\sum_{j=1}^{N} s_j^2}$ (where N is the number of **participants** and s_j is the standard deviation for the jth participant) was calculated. **To** determine the agreement of the measurement method, the 95% **confidence interval** was calculated to assess observer bias $d \pm t_{0.05,n-1}\frac{s}{\sqrt{n}}$ (where d is the mean of the differences between measurements by two observers for the same **participant**, s is the standard deviation of the differences between measurements by two observers, n is the sample size and $t_{0.05,\ n-1}$ is the t-Student value with n-1 degrees of freedom and 95% confidence). In addition, the mean and **confidence intervals** of the coefficients of variation determined by each of the eight observers for the same **participant** were calculated.

Coefficient of variation of stroke rate

For each event, the coefficient of variation of stroke rate (CV_{SR}), 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 analysed.

Statistical analysis

Values are expressed as mean ± standard deviation. The Shapiro Wilk test was used to check the hypothesis of normal distribution. One-way analysis of variance (ANOVA) was applied to test the dependences of V, SL, SR and CV_{SR} on the four swimming techniques (butterfly, breaststroke, backstroke, freestyle) and on the performance **standard** (Olympic and National). Two-way ANOVA was applied to test the interaction effects [four swimming techniques x performance **standard**]. The student Newman-Keuls post-hoc test was then applied **to identify particular differences**. For each of the four swimming techniques, $CV_{SR}1$ and $CV_{SR}2$ were compared using one-way ANOVA. For each event, the relationships between ΔCV_{SR}, ΔV, ΔSR, and ΔSL were analysed using Pearson's **product-moment correlation coefficient**. Data analysis was performed with Matlab 6.5 Stats Toolbox (The MathWorks, Inc.) and STATISTICA 5.1 (StatSoft France, Inc.). The threshold for significance was set at level $\alpha = 0.05$ for all tests.

Results

The Olympic semi-finalists were older (23 ± 4 vs. 20 ± 3 yrs, $p < 0.01$) and specifically for each event, butterfly (23 ± 4 vs. 21 ± 2 yrs, $p < 0.05$), breastroke (22 ± 3 vs. 19 ± 3 yrs, $p < 0.05$) and freestyle (23 ± 5 vs. 20 ± 2 yrs, p=0.0504). It was hypothesized that **stroke length, stroke rate** and **the coefficient of variation of stroke rate** depend on the four swimming techniques being performed and the **standard** of performance. Results of the comparisons between the Olympic-**standard** (group O) and National-**standard** (group N) swimmers are presented in Table 1. Comparisons between the four swimming techniques are presented in Table 2 and Figure 3.

Swimming speed

The two groups of swimmers differed according to standard (ANOVA: variable × **standard** of performance, Table 1) **technique** (ANOVA: variable × swimming technique, Figure 3), **performances** ($p < 0.001$), swimming **speed** ($p < 0.001$) and variation in the swimming **speed** between the first and the second 100 meters ($p < 0.001$). **Overall** (Olympic and National groups analysed together), V1 were (1.50 ± 0.05; 1.44 ± 0.04; 1.28 ± 0.04; 1.63 ± 0.02 $m.s^{-1}$), V2 (1.39 ± 0.06; 1.38 ± 0.05; 1.22 ± 0.05; 1.61 ± 0.09 $m.s^{-1}$) and ΔV (0.11 ± 0.02; 0.06 ± 0.02; 0.06 ± 0.02; 0.01 ± 0.08 $m.s^{-1}$), for butterfly, backstroke, breaststroke and freestyle respectively. ΔV butterfly **was greater** than ΔV backstroke, ΔV breaststroke and

ΔV freestyle. ΔV freestyle **was lower** than ΔV butterfly, ΔV breaststroke, and ΔV backstroke ($p < 0.001$).

Stroke length

Standard of performance (ANOVA: variable × **standard** of performance, Table 1) and type of swimming **technique** (ANOVA: variable × swimming technique, Figure 3) **affected** SR1, SL2, and ΔSL ($p < 0.05$). For the overall population (Olympic and National groups analysed together), SL1 were (1.83 ± 0.13; 2.19 ± 0.14; 2.15 ± 0.21; 2.21 ± 0.17 m), SL2 (1.73 ± 0.12; 2.13 ± 0.15; 1.98 ± 0.21; 2.15 ± 0.15 m) and ΔSL (0.09 ± 0.04; 0.06 ± 0.08; 0.17 ± 0.09; 0.06 ± 0.07 m) for butterfly, backstroke, breaststroke and freestyle respectively. ΔSL was higher for breaststroke than butterfly, backstroke and freestyle ($p < 0.01$). When the results for the four 200m events were analysed together, SL1 and SL2 were greater in group O (2.12 ± 0.24; 2.03 ± 0.24 vs. 2.05 ± 0.21; 1.96 ± 0.21; $p < 0.05$). Specifically, 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

Standard of performance (ANOVA: variable × **standard** of performance, Table 1) and type of swimming technique (ANOVA: variable × swimming technique, Figure 3) **affected** SR1, SR2, and ΔSR ($p < 0.05$). SR1 were (49.37 ± 3.73; 39.91 ± 3.03; 35.98 ± 3.89; 44.72 ± 3.69 $s.mn^{-1}$), SR2 (48.39 ± 3.66; 39.09 ± 3.33; 37.24 ± 3.88; 43.94 ± 3.08 $s.mn^{-1}$) and ΔSR (0.98 ± 1.41; 0.81 ± 1.52; -1.25 ± 1.82; 0.78 ± 1.43 $s.mn^{-1}$), for butterfly, backstroke, breaststroke, and freestyle respectively. ΔSR was lower for breaststroke than butterfly, backstroke and freestyle ($p < 0.001$). When the results for the four 200m events were analysed together, group O exhibited higher SR1 and SR2 (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 ($p < 0.05$), Table 1.

Stroke rate variability

Swimming technique (ANOVA: variable × swimming technique, Table 2), **standard** (ANOVA: variable × **standard** of performance, Table 1) and the interaction of these two factors (ANOVA: variable × [**standard** of performance × swimming technique]) **affected** $CV_{SR}1$, $CV_{SR}2$, and ΔCV_{SR} ($p < 0.01$). $CV_{SR}1$ for butterfly **was lower** than $CV_{SR}1$ for backstroke ($p < 0.05$) and breaststroke ($p < 0.01$). $CV_{SR}2$ for breaststroke **was greater** than $CV_{SR}2$ for backstroke ($p < 0.05$) and butterfly ($p < 0.05$). ΔCV_{SR} for backstroke **was greater** than ΔCV_{SR} for breaststroke ($p < 0.05$). When the results for the four 200m events were analysed together, $CV_{SR}1$ and $CV_{SR}2$ were lower 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). For the overall population $CV_{SR}1$ was greater than $CV_{SR}2$ for butterfly, backstroke and freestyle ($p < 0.01$, table 2). For backstroke and freestyle respectively, ΔCV_{SR} was positively correlated with ΔV (r=0.67; 0.69, $p < 0.01$), and ΔSR (r=0.73; 0.74, $p < 0.01$) and negatively correlated with ΔSL (r= -0.57; -0.67, $p < 0.01$). For breastroke ΔCV_{SR} was positively correlated with ΔSR and negatively correlated with ΔSL respectively (r=0.46; -0.64, $p < 0.05$). Evaluation of **reproducibility** and agreement did not reveal any bias in the measurement method used to determine stroke rate, stroke-per-stroke. The mean of the coefficients of variation determined by eight observers for the same **participant** was 7.4% (95% interval of confidence: 7.1-7.8%).

Discussion

The purpose of this study was to compare kinematics and **stroke rate variability** in female 200-m swim events. The main findings were: (i) **stroke length** and **stroke rate** were different for the four techniques. **Stroke length** was shorter for butterfly and longer for backstroke and freestyle; (ii) **stroke length** and **stroke rate** were influenced by **standard**.

The Olympic-**standard** swimmers exhibited faster backstroke and longer freestyle strokes; (iii) **Stroke rate variability** depended on **event** and **standard**. Olympic-standard swimmers exhibited less **stroke rate variability** in backstroke and freestyle. In butterfly, backstroke and freestyle, **stroke rate variability** decreased during the second 100-m in the overall population.

Stroke length and stroke rate: Between-stroke comparisons

Stroke length were longer for alternating arm strokes compared with simultaneous arm strokes, as previously reported (Craig and Pendergast, 1979; Craig *et al*., 1985; Chengalur and Brown, 1992; Keskinen and Komi, 1993; Chollet *et al*., 1996; Chatard *et al*., 2001a,b). For alternating strokes, one arm is in the propulsion phase while the other is in the recovery phase (Seiffert *et al*., 2004a,b; 2005). These alternate actions, together with a profiled body position, ensure a continuous motor effect at low energy cost (Costill *et al*., 1992; Wakayoshi *et al*., 1995). 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, **allow** a longer **stroke length** in freestyle and backstroke (Schleihauf *et al*., 1988; Costill *et al*., 1992; Lerda and Cardelli, 2003). Although most studies indicate that **stroke length** is greater for backstroke, then in declining order for freestyle, butterfly, and breaststroke (Craig and Pendergast, 1979; Craig *et al*., 1985; Chengallur and Brown, 1992; Chollet *et al*., 1996), our results and those published recently by others (Chatard *et al*., 2001a,b; Girold *et al*., 2001) show that the decreasing order is freestyle, backstroke, breaststroke, and butterfly. Since the early work of Craig and Pendergast, (1979), the increase in **stroke length** 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 (Chollet *et al*., 2004; Seiffert *et al*, 2004a,b).

The changes observed in **stroke rate** over the last 35 years (East, 1970; Craig and Pendergast, 1979; Craig *et al*., 1985; Chengalur and Brown, 1992; Chollet *et al*., 1996; Chatard *et al*., 2001a, b; Girold *et al*., 2001), illustrate a similar trend. Since 1970, small **stroke rate** 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 **stroke rate** 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, **stroke rate** must rise above a minimal threshold. Unlike freestyle and breaststroke, the butterfly stroke induces biomechanical constraints hindering full **exploitation** of the gliding phase. Indeed, in breaststroke, the centre of gravity is lower during the phases when the arms move forward, enter the water, and push downward (Martins-Silva *et al*., 1997). Furthermore, major intra-stroke variations in the **speed** of the centre of mass are correlated with less efficient swimming (**Vilas Boas, 1996; Barbosa *et al*., 2005**). Swimmers thus adapt their strategy to limit the **loss of speed** during the non-propulsive phases by better coupling the propulsive actions of their propulsive segments (Martins-Silva *et al*., 1997; Chollet and Boulesteix, 2001). 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 (Schleihauf *et al*., 1988). Thus the best backstroke swimmers adapt their strategy by moving their arm out of the water more rapidly (Lerda and Cardelli, 2003), which probably implies a more rapid **stroke rate**.

Stroke length and stroke rate: between-group comparisons

The Olympic swimmers had longer **stroke length** than the National-**standard** swimmers, confirming data reported by others (East, 1970; Craig and Pendergast, 1979; Craig *et al*., 1985; Thomson *et al*., 2000). **Stroke length** has been interpreted as an index of high propulsive **effectiveness** (Wakayoshi *et al*., 1993, 1995) resulting from greater propulsive force generated by the arms and legs (higher peak force) (Chollet *et al*., 2004), associated with more effective coordination patterns between propulsive and gliding phases (Chollet and Boulesteix, 2001; Chollet *et al*., 2004; Seiffert *et al*., 2004b; Seiffert *et al*., 2005). When the results for the four 200m events were analysed together, the Olympic swimmers were also characterized by higher **stroke rate**, which persisted throughout the race. These results are in line with data from many studies **that** have identified **stroke rate** as a factor of performance (Chengalur and Brown, 1992; Thomson *et al*., 2000; Chatard *et al*., 2001a, b; Girold *et al*., 2001). The capacity to maintain a high **stroke rate** until the end of the race is associated with muscular power (Wakayoshi *et al*., 1993), neuromotor control and muscular endurance (Keskinen and Komi, 1993). Like others (Chengalur and Brown, 1992; Chatard *et al*., 2001a) 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 (Lerda and Cardelli, 2003).

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 **stroke rate** or **stroke length**. This **contradicts** data reported by others (Craig *et al*., 1985; Chengalur and Brown, 1992; Thomson *et al*., 2000; Chatard *et al*., 2001b; Girold *et al*., 2001). The discordance could be related to the study populations, since it is known that **swimming speed**, **stroke rate**, and **stroke length** are not linearly related (Craig and Pendergast, 1979; Keskinen and Komi, 1993; Wakayoshi *et al*., 1995). This **could** explain why **differences** between swimmers **of different standard** (for example Olympic series swimmers versus finalists) are no longer observed in populations **of similar standards** (for example semi-finalists and finalists).

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

Our original approach was to analyze **variability of stroke rate** in a population of elite Olympic- and National-**standard** 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 confidence interval** of the measurement method, indicating the absence of a methodological bias in the statistical interpretation (Bland and Altmann, 1986). The greater variability in the breaststroke rate could be explained by changes in the coordination patterns often observed in this stroke (Seiffert *et al*., 2004a, b). The breaststroke is characterized by a greater time lag between arm and leg movements and a longer glide time **that** enable the swimmers to shorten or lengthen transition phases between arm and leg movements (Chollet *et al*., 2004). The underwater recovery movement of the arms and legs creates drag at high swim **speed** (Kolmogorov and Duplishcheva, 1992; Chollet *et al*., 2004). The propulsive forces of the limbs are also greater than in the other three strokes (Chollet *et al*., 2004). Thus logically, coordination patterns could vary during the same race. During the first hundred meters, production of faster **speed** associated with a **lower stroke rate** is probably related to the generation of greater propulsive forces (Martin-Silva *et al*., 1997; Aujouanet *et al*., 2006) and more **effective** swimming technique allowed by lesser neuromuscular fatigue (Craig and Pendegast, 1979; Alberty *et al*., 2003; Aujouanet *et al*., 2006). Higher propulsive forces associated with more **effective** swimming technique and coordination (optimized duration of glide phase and better continuity in the arm leg action) lead to **greater speed and longer stroke length (Craig *et al*., 1985**; Chollet *et al*., 1999; Soares *et al*., 1999). For Chollet *et al*., (2004), better 200m swimmers favour a streamline position during the glide phase to maintain their **speed**. Less rapid **stroke rate** (Wakayoshi *et al*., 1995) and better continuity in the propulsive phases of the arm and leg action probably **reduce** intracyclic variations in **speed and similarly, reduce** energy cost (Vilas-Boas, 1996). **Conversely**, at the end of the race, the swimmer **increases** propulsion by increasing **stroke**

rate. This would induce greater **stroke rate variability** for breaststroke than for the other three strokes. **In** butterfly, the coordination pattern would remain stable for different swimming **speeds** (Chollet and Boulesteix, 2001). This could explain the lower **coefficient of variation of stroke rate** compared with the other strokes. In butterfly, swimmers have to achieve a precise synchronization between **breathing** and three movements (one-arm and two-leg), each leg movement **comprising** an ascending phase and a descending phase (Costill *et al*., 1992; Chollet and Boulesteix, 2001). This **leaves** less room for modifying coordination patterns. The variabilities observed for backstroke and freestyle **were greater** than in butterfly, suggesting that, **as observed** in running and walking, a major part of the variability depends on movement asymmetry (Newell and Corcos, 1993) and the requirement **successively to** redirect the centre of mass forward after each lateral movement of the limbs (Donelan *et al*., 2001; 2004). The Olympic swimmers **exhibited** less **stroke rate variability** in freestyle and breaststroke races, providing confirmation of the lesser movement variability in the most skilled athletes performing high-**speed** tasks strongly influenced by movement asymmetry (Newell and Corcos, 1993; Brisswalter and Mottet, 1996; Danion *et al*., 2003; Davids *et al*., 2003). Lesser **stroke rate variability** was a characteristic feature observed in the backstroke and freestyle Olympic-**standard** swimmers.

Sidney *et al*. (1999) also showed 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 **standard** and motor skill (Newell and Corcos, 1993; Sekiya *et al*., 1997; Danion *et al*., 2003; Davids *et al*., 2003). In runners, it has also been demonstrated (Candau *et al*., 1995), that stride rate variability and stride rate are related to energy cost. For runners, stride variability has been found to be associated with increased **speed** (Nilsson **and** Thorstensson, 1987, 1989; Candau *et al*., 1995). In the same way, we found that at higher **speeds**, Olympic-**standard** swimmers exhibited less **stroke rate variability** compared with National-**standard** swimmers.

Variability in stroke frequency: fatigue effects

The decreased **stroke rate variability** observed in the overall population during the second 100-m of the butterfly, backstroke and freestyle events does not confirm the increased **stroke rate variability** observed with fatigue in walking and running events (Candeau *et al*., 1995; **Slawinski** *et al*., 2001; Yoshino *et al*., 2004). In these events, increasing **stroke rate variability** with fatigue was interpreted as the consequence of the perturbation of the anterioposterior and vertical movements of the centre of mass (**Slawinski** *et al*., 2001). These additional **excursions** of the **centre of mass** involve in an increase of kinetics, and potential energy variation, which provoke an increase **in** mechanical work (**Slawinski** *et al*., 2001). In our study, **stroke rate variability** correlated with decreased **speed** and **stroke rate**, in agreement with studies showing that **stroke rate variability** is rate and **speed** dependent (Nilsson and Thorstensson, 1987, 1989; Candau *et al*., 1995). An experimental comparison between changes in **stroke rate variability arising from** fatigue at constant rate and **speed** would be useful to measure the effects of neuromuscular and metabolic fatigue on the course of **stroke rate variability**. Similarly, the lower coefficient **stroke rate variability** observed in the butterfly race was not correlated with any kinematic **measure** and cannot be appropriately interpreted without complementary measurements concerning, for instance, energy cost or intracyclic **speed** variations.

Tentative of interpretation using the dynamic systems theory

In the dynamic systems theory, movement is considered as an emerging property **that** results from the interaction between the self-organization capacity of the neuromusculoskeletal system, represented in our study by individual skill or **standard**, and the task requisites, represented in our study by the **four swimming events** (Schöner and Kelso, 1988; Newell and

Corcos, 1993; Brisswalter and Mottet, 1996; Davids *et al*., 2003). The **measures stroke length, stroke rate** and **speed** were considered as control **characteristics that correspond** to a specific coordination pattern (Seifert *et al*., 2004a, b). This coordination pattern emerges from the swimmers' adaptation to the biomechanical requisites of each type of swimming stroke (Chollet *et al*., 2004). Using the dynamic systems theory **to improve understanding of** 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 **that** set specific limits for self-organization. The lower variability in backstroke and freestyle observed in the Olympic swimmers could thus be interpreted as stability and optimal **effectiveness** obtained by system coupling (Newell and Corcos, 1993; Brisswalter and Mottet, 1996; Masani *et al*., 2002; Danion *et al*., 2003; Donelan *et al*., 2001; 2004). Considering the entire population, the higher variability **in** breastroke can be interpreted as the capacity of elite swimmers to exploit the high dimensionality offered by the motor system's many degrees of freedom. Several studies have indeed shown that skilled performers can freeze or unfreeze the degrees of freedom in the chain of movement as the prevailing task constraints demand (Newell and Corcos, 1993; Davids *et al*., 2003).

Conclusion

Faster swimming observed in Olympic semi-finalists was associated with differences in **stroke rate, stroke length** and **stroke rate variability**. These differences were dependent on the interaction between the biomechanical requisites of the task (swimming techniques) and individual skill. **Stroke rate variability was greatest for breaststroke with** freestyle, backstroke, and butterfly in decreasing order. Female Olympic swimmers were characterized **by greater** backstroke rate, longer freestyle **stroke length**, and less **stroke rate variability**. For backstroke, breastroke and freestyle, a lesser **stroke rate variability** during the second one hundred meters was correlated with decreased **speed** and **stroke rate**. The findings from this exploratory study open the perspective of experimental and confirmatory analysis of stroke rate variability by imposing fixed **stroke rate** and **stroke length**. This would enable a better understanding of the effects of voluntary modulation of **stroke rate** or amplitude to adapt performance to competitors or fatigue during the course of the race.

LEGEND OF FIGURES

Figure 1. Video recording set up (SZ, start zone; TZ, turn zone; FZ, finish zone; T1, T2, T3 **and** 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.

Figure 3. Performance **measures** with confidence intervals (95%) for the four swimming techniques: butterfly, backstroke, breaststroke, freestyle. Swim **speed** (V1, V2 in $m.s^{-1}$), stroke length (SL1, SL2 in m), stroke rate (SR1, SR2 in $s.min^{-1}$). * **Different** $\alpha = 0.05$.

Figure 1.

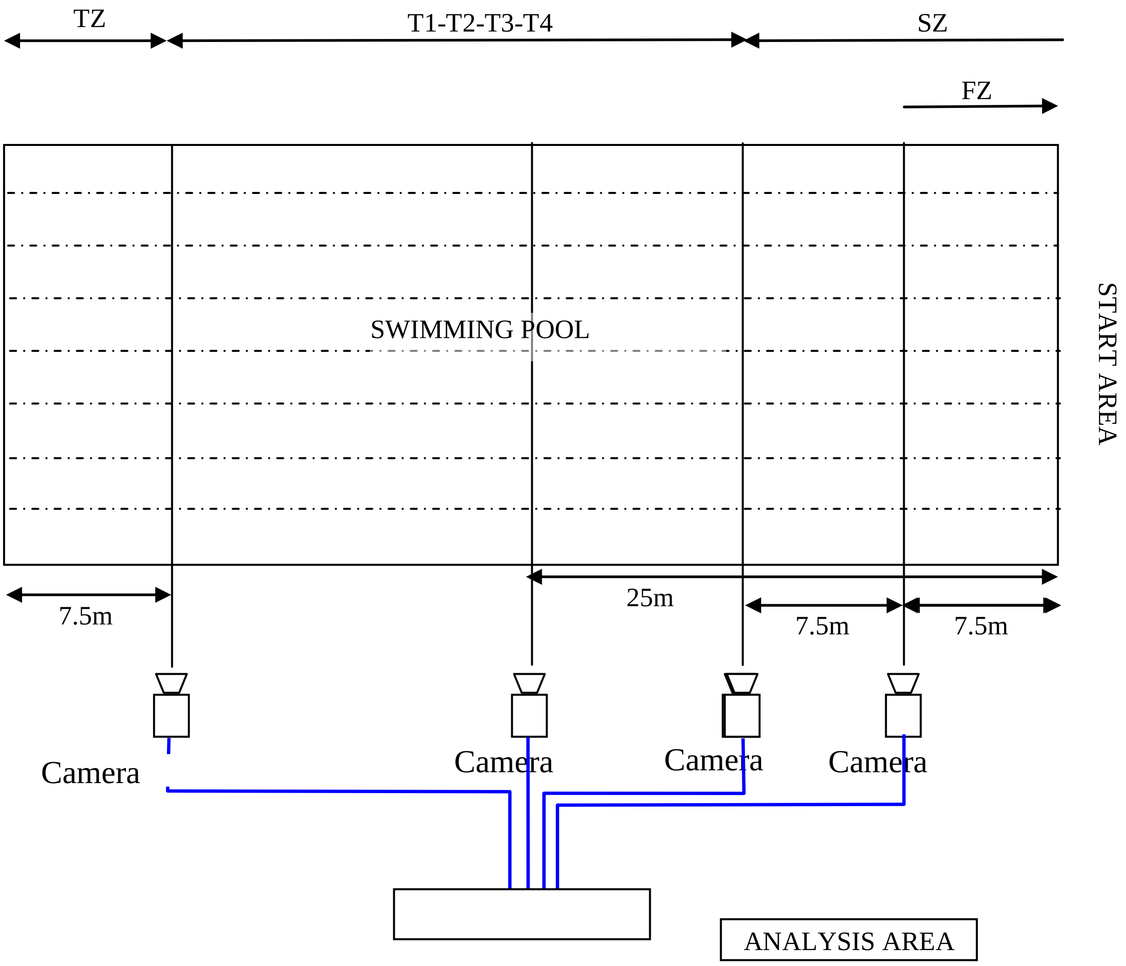
TZ
T1-T2-T3-T4
SZ
FZ
SWIMMING POOL
START AREA
7.5m
25m
7.5m
7.5m
Camera
Camera
Camera
Camera
ANALYSIS AREA

Figure 2.

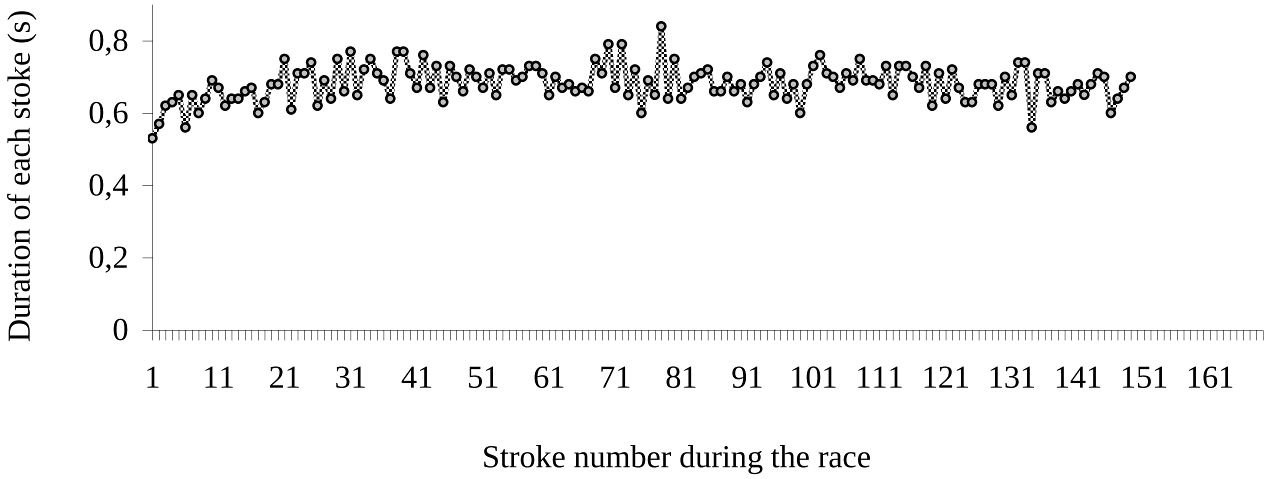
Duration of each stoke (s)
0,8
0,6
0,4
0,2
0
1 11 21 31 41 51 61 71 81 91 101 111 121 131 141 151 161
Stroke number during the race

Figure 3.

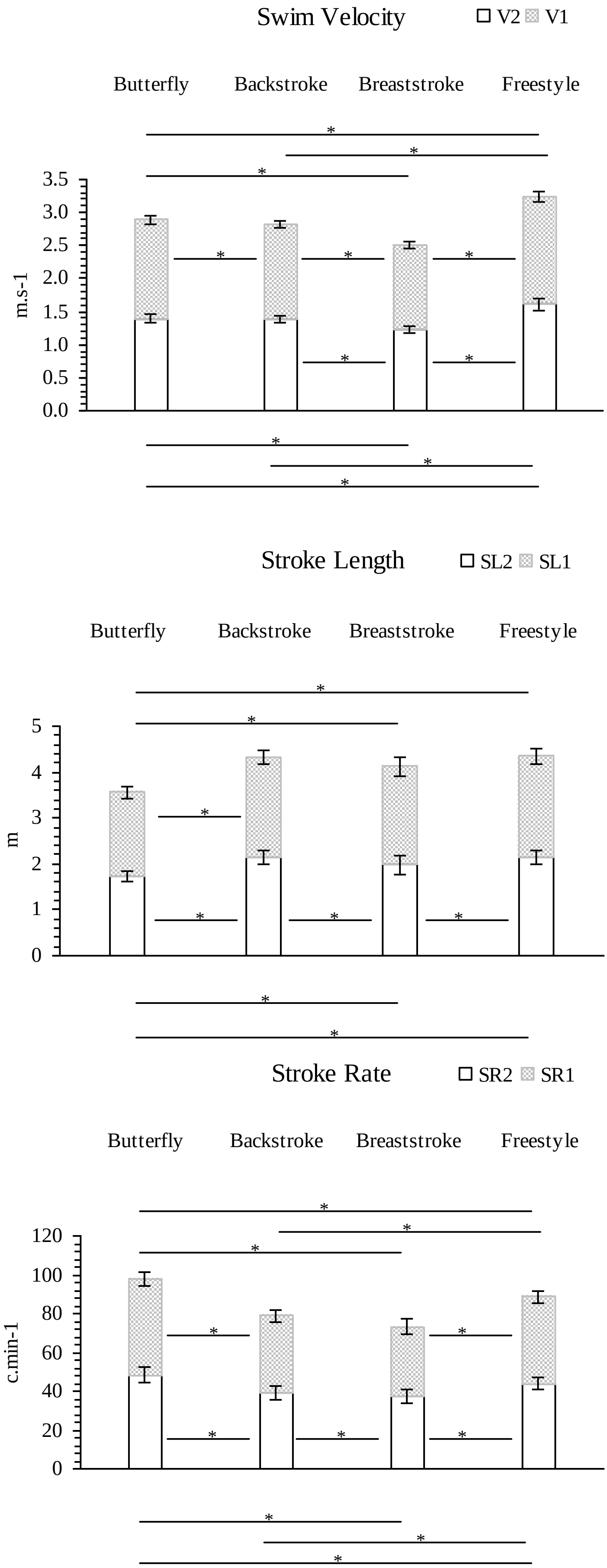
Swim Velocity
V2
V1
Butterfly
Backstroke
Breaststroke
Freestyle
m.s-1
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
Stroke Length
SL2
SL1
Butterfly
Backstroke
Breaststroke
Freestyle
m
5
4
3
2
1
0
Stroke Rate
SR2
SR1
Butterfly
Backstroke
Breaststroke
Freestyle
c.min-1
120
100
80
60
40
20
0

Table 1. Performance **characteristics** for group O (Olympic semi-finalists) and group N (French national championship semi-finalist). **Values are mean (standard deviation).**

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 (**s**.min^{-1})	O	50.1 (4.1)		41.0 (2.8)		36.6 (4.9)		44.3 (4.0)	
	N	48.5 (3.2)		38.7 (2.9)	*	35.7 (3.1)		44.3 (2.9)	
SR2 (**s**.min^{-1})	O	49.3 (4.0)		40.7 (3.2)		37.9 (4.2)		44.1 (3.6)	
	N	47.3 (3.0)		37.4 (2.6)	**	36.8 (3.7)		43.7 (2.5)	
ΔSR (**s**.min^{-1})	O	0.8 (1.3)		0.3 (1.3)		-1.3 (1.7)		0.3 (1.0)	
	N	1.2 (1.5)		1.3 (1.6)		-1.0 (2.2)		0.7 (1.4)	
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)		0.07 (0.07)		0.18 (0.07)		0.08 (0.05)	
	N	0.11 (0.04)		0.05 (0.08)		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)	

Swim **speed**, stroke rate, stroke length and coefficient of variation for the first and the second 100 m and for the differences.* **Difference** between group O (Olympic semi-finalists) and group N (French national championship semi-finalist), $p < 0.05$; ** **Difference** between group O and group N, $p < 0.01$; *** **Difference** between group O and group N, $p < 0.001$.

Table 2. Coefficients of variation for the four swimming techniques, butterfly, backstroke, breaststroke, freestyle.

	Butterfly	Backstroke	Breaststroke	Freestyle
$CV_{SR}1$ (%)	4.8 (0.9) $^{\#, \dagger}$	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)

Values are means (standard deviations). $^{\#}$ Different from backstroke, $p<0.05$ ($^{\#\#}$, $p<0.01$); † different from breaststroke, $p < 0.05$ (††, $p<0.01$); * different from butterfly, $p < 0.05$ (**, $p<0.01$).

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