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Influence of stroke rate on coordination and sprint performance in elite male and female swimmers

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This study investigated the effects of gender and the manipulation of the preferred stroke rate on swimming performance and arm coordination in elite front crawl swimmers. Nineteen swimmers performed a dual task, that is, imposed stroke rate and maximal speed. They swam nine 25-m trials at maximal speed twice: one trial at the preferential stroke rate, one trial at maximal stroke rate and seven trials at stroke rates between 41 and 59 cycles/min imposed by an Aquapacer. Stroke rate, arm stroke phases, and arm coordination were computed from an inertial measurement unit on each forearm and one on the sacrum. Time on the 25-m was recorded to assess swimming speed. Results indicated that the error between the imposed and performed stroke rates was lowest at the preferred stroke rate for women. An increase in stroke rate led to an increase in swimming speed and the index of coordination, but these changes could be influenced by the preferred stroke rate. Individual analysis revealed that some swimmers exhibited higher flexibility (larger range of stroke rate) around their preferred stroke rate. This stroke rate flexibility appeared more functional in swimmers who reached higher speeds when swimming at the maximal stroke rate than at the preferred stroke rate.

KEYWORDS
freestyle, functional variability, preferred stroke rate, sprint

1 | INTRODUCTION

Swim speed is the product of stroke length and stroke rate, and stroke rate was found to contribute most to reaching high swimming speeds.[1] Numerous studies have investigated the effect of speed changes on the stroking parameters (ie, stroke length and stroke rate) and arm coordination in elite front crawl swimmers.[2-5] Coordination between propulsive actions of the left and right arms is highly correlated to stroke rate, swimming speed, speed fluctuations, and power output.[5,6] Three coordination modes are usually observed in front crawl swimming and quantified by an index of coordination (IdC[7]). The catch-up mode corresponds to a lag time between the propulsive phases of the two arms. The opposition mode corresponds to continuity between the beginning of the pull phase of one arm while the other arm finishes its push phase. The superposition mode corresponds to an overlap in the propulsive phases. Through an incremental protocol (from 1500-m to 50-m) but no constraint for stroke rate, Seifert et al[2] observed that front crawl swimmers, whatever the skill level or gender (international, national or regional; male or female), increased their swimming speed and stroke rate and changed their arm coordination (assessed by the IdC). In particular, elite male swimmers switched from the catch-up coordination mode at slow pace (IdC $< 0\%$) to superposition mode at sprint pace (IdC $> 0\%$), with the coordination transition occurring near 1.80 m/s and a stroke rate of 45-50 cycle/min.

These findings were also observed in swimming competition, as high speed was associated with high stroke rate.[8] Moreover, the elite swimmers attempted to compensate the diminution of stroke length by increasing stroke rate as a strategy to limit the speed decrease through the race.[8] Thus, stroke rate manipulation during paced exercise was introduced to stabilize motor coordination.[9] Training swimmers to broaden their range of stroke rates and/or their range of coordination modes is nevertheless not a common concern or strategy for coaches, as they often try to stabilize a given number of strokes or a targeted time that swimmers should maintain through the lap or race. However, various stroke rates and their management have been observed within and between laps during competition[10,11] and between swimmers,[12] suggesting that several profiles of stroke rate management could lead to high swimming performances.

Yet, no published studies have explored the impact of stroke rate manipulation on swimming performance or the biomechanical, energetic, and motor control aspects in a maximal effort for elite swimmers (ie, international swimmers with their best swimming times near ~90% of the World Record). The only studies investigating the impact of stroke rate manipulation have concerned young swimmers[13] and national and regional swimmers.[9,14-17] Concerning the energetics, McLean et al[17] manipulated the stroke rate around the preferential stroke rate (−20%, −10%, 0%, +10%, and +20%) for a submaximal effort (swimming speed at 1 m/s) with a duration leading to steady-state oxygen consumption (4-5 minutes). The main findings were significant increases in oxygen consumption (from 11% to 16%), heart rate (from 4% to 6%), and rate of perceived exertion (from 15% to 30%) when the stroke rate was reduced but not when it was increased. McLean et al[17] hypothesized that the reduced arm stroke rate was compensated by increased leg beat kicking, that is, the kicking rate increased from 2.6 kick/s at the preferential stroke rate to 3.8 kick/s for a stroke rate 20% lower than this preferred stroke rate. However, previous studies have shown that a high kicking rate results in a high energy cost of locomotion,[16,18] suggesting that when stroke rate is manipulated, the consequences for the leg kicking rate should also be considered. When stroke rate was manipulated during high-velocity training (and not assessed during testing session), Termin and Pendergast[19] showed that collegiate swimmers can improve biomechanics and metabolism ultimately leading to enhanced swim performances without dry-land training, over-distance training, or a taper.

Concerning the effect of stroke rate manipulation on swimming performance and arm coordination, Potdevin et al[15] showed that during a test of 5 x 25-m swum as fast as possible with an imposed stroke rate (35, 40, 45, 50, and 55 cycle/min), 100% of national and regional swimmers exhibited catch-up coordination when the imposed stroke rate was between 35 and 45 cycle/min, and 54.5% of national swimmers exhibited catch-up coordination and 45.5% superposition coordination when the imposed stroke rate was between 50 and 55 cycle/min. Conversely, regional swimmers tended to switch more quickly to superposition mode, as 62.4% of them showed superposition and only 37.6% showed catch-up when the imposed stroke rat was 55 cycle/min.[15] In line with the constraint-led approach to motor control,[20] Potdevin et al[15] suggested that a high level of constraint (ie, high stroke rate) reduces the range of coordination possibilities (within and between individuals), whereas a low level of constraint (ie, low stroke rate) allows several motor solutions to achieve the task goal. Nevertheless, no published data are available for elite swimmers.

More recently, the ecological dynamics framework has been applied to motor control,[21-24] the functional role of variability in movement coordination (within and between individuals) has been emphasized, with the interaction of a set of constraints (ie, organismic, task, and environment[20]) taken into account. From this perspective, movement coordination variability may reflect the behavioral flexibility of individuals as they adapt to constraints apart from their preference in order to test whether they can achieve a task goal.[25] In swimming, behavioral flexibility can be investigated by assessing the range of stroke rates and movement coordination modes apart from the preferred stroke rate and preferred coordination mode.[16,26] In front crawl, elite swimmers demonstrated a higher energy cost of locomotion when performing at maximal glide (ie, associated with a lower stroke rate and higher IdC) and minimal glide (ie, associated with a higher stroke rate) than in the preferred glide condition.[16] However, this study examined only the effects of "extreme" gliding conditions on motor coordination at submaximal swimming speed and not a wide range of stroke rates during maximal effort. The effect of stroke rate (or glide) manipulation on swimming performance and motor coordination thus requires further investigation as it is still unclear whether an increase in stroke rate leads to an increase in swimming speed and changes in arm coordination independently of the preferred stroke rate and whether these modifications are influenced by the preferred stroke rate.

Finally, the literature contains no reports of differences of stroke rate between genders in 50, 100, and 200-m freestyle[10,27-30] whereas men and women exhibited difference of arm coordination during sprint events.[2,31] Therefore, clarification is necessary to understand how gender and individual preferences can explain various stroke rate and arm coordination during sprint events.

The aim of our study was to investigate the effects of gender and of stroke rate manipulation on swimming performance and arm coordination in elite front crawl swimmers and how preferred stroke rate could influence the adaptation of swimmer's behavior. We hypothesized that (a) the increase in stroke rate would lead to an increase in swimming speed and the IdC, (b) stroke rates performed away from the preferred stroke rate would lead to lower swimming performances, (c) stroke rate flexibility would be lower in women due to their difficulties in matching the targeted stroke rate when high values are imposed, and (d) some swimmers would not be able to significantly increase their stroke rate above the preferred stroke rate when the maximal stroke rate was requested (reflecting low stroke rate flexibility) and, when they could do it, some would not swim faster (reflecting non-functional stroke rate flexibility).

2 | METHODS

2.1 | Participants and protocol

Eleven male swimmers (age: 20.7 ± 3.2 years, height: 185.2 ± 2.3 cm, mass: 75.8 ± 3.6 kg) and eight female swimmers (age: 21.7 ± 3.7 years, height: 172.0 ± 5.6 cm, mass: 60.9 ± 6.9 kg) voluntarily participated in this study. Those swimmers were recruited because of their top level in short distance competition (50, 100, and 200-m). Half of them were front crawl specialist and the other half primarily swim butterfly, backstroke, and breaststroke but swim front crawl in competition as secondary swimming technique. All the swimmers trained 10 times/wk, and their best performance in the 100-m front crawl in a long course (50-m) swimming pool was 52.15 ± 1.40 seconds for men, corresponding to 88.6 ± 2.9% of the men's World Record, and 58.15 ± 2.25 seconds for women, corresponding to 88.7 ± 2.9% of the women's World Record. Participants were informed of the study procedures and signed a written consent form, and the study was approved by the Rouen university Ethics Committee. Moreover, the procedures described below followed the Declaration of Helsinki.

2.2 | Data collection

The protocol comprised two test sessions on separate days and each session was preceded by an individual warm-up. In each session, participants swam nine 25-m trials in a 25-m pool at maximal speed with one trial at preferential stroke rate (SR_P), one trial at maximal stroke rate (SR_M), and seven trials at imposed stroke rates (41, 44, 47, 50, 53, 56, and 59 cycles/min, P1-P7) in randomized order. SR_P corresponded to the swimmers' spontaneous stroke rate without any instruction; however, this stroke rate was checked to ensure that it was close to that performed during the clean swimming part of the first lap in competitive events. As the swimmers were placed in a *dual task* (imposed stroke rate and maximal speed), they were instructed to respect the imposed stroke rate first and then swimming at maximal speed. Each stroke rate was imposed by a pacing device (Aquapacer Tempo Trainer Pro® Finis, Inc) placed under the cap.[32] For each trial, the swimmers were instructed to achieve an underwater wall push-off of 3-5-m with one or two breaths during the 25-m. A 4-minute recovery between trials was allocated to avoid fatigue. Before starting the protocol, the swimmers had a familiarization session and trained at the imposed stroke rates using the pacing device. Moreover, these swimmers were already familiarized with the tempo trainer, which was used to pace their stroke rate during regular training.

The swimmers were equipped with three inertial measurement units (IMUs, Hikob Fox©): one IMU on each forearm and one IMU on the sacrum. Waterproofing, fixation, and calibration procedures were carried out according to Dadashi et al[33] and Guignard et al.[34] Each IMU was composed of a three-dimensional accelerometer (±16 G), a three-dimensional gyroscope (±1200/s) and a three-dimensional magnetometer (±8.1 Gauss) and recorded at 100 Hz. The three axes of the IMU were aligned with the swimmer such that the x-, y-, and z-axes corresponded, respectively, to the mediolateral, anteroposterior, and vertical axes. Last, an operator followed the head of the swimmer with a camera fixed on a trolley (as previously done by Seifert et al[2]) to provide a lateral underwater view of the swimmer in order to supervise the IMU processing, to check the cleaned cycles of the swimming part used for the data analysis and to check the leg beat kicking.

2.3 | Data analysis

According to Chollet et al[7] the front crawl stroke cycle can be divided into four phases (ie, catch and glide, pull, push, and recovery), which can be grouped into propulsive (ie, pull and push) and non-propulsive phases (ie, catch and glide and recovery). Following the procedures of Dadashi et al,[33] the pull, push, and recovery phases were identified based on the accelerometric and gyroscopic signals from the IMUs positioned at the lower arm and sacral levels. The mediolateral angular velocity of the lower arm was used to detect the hand entry into the water (as previously done by Guignard et al[34]). This corresponds to the first observable peak in the raw gyroscopic data between the instant of maximum angular velocity (corresponding to the half arm recovery) and the start of the pull. From there, we computed the duration of one stroke cycle (corresponding to the absolute time separating one hand water entry to the next).

The coordination between the two arms was computed by the IdC.[7] The IdC corresponds to the mean of IdC_1 (ie, the lag time between the beginning of the propulsive phase in the first right arm stroke and the end of the propulsive phase in the first left arm stroke) and IdC_2 (ie, the lag time between the beginning of the propulsive phase in the second left arm stroke and the end of the propulsive phase in the first right arm stroke). The IdC is expressed in percentage of the cycle duration: IdC >0% corresponds to superposition mode, IdC <0% corresponds to catch-up mode and IdC =0% corresponds to opposition mode.[7] To avoid start and finish effects, only the clean swimming cycles were kept; moreover, one cycle at the beginning and one cycle at the end of the 25-m bouts were systematically removed from the analyses.

The stroke rate (SR, in cycle/min) was computed as follows:

$$\mathrm{SR} = \frac{1}{T} \tag{1}$$

with T = the cycle duration.

This performed stroke rate could differ from the stroke rate imposed by the Aquapacer ($\mathrm{SR_{th}}$). This error was quantified as follows:

$$\mathrm{Error\ SR} = \left| \frac{\mathrm{SR_{th}} - \mathrm{SR}}{\mathrm{SR_{th}}} \right| * 100$$

Then, for individual comparison, the SR was normalized ($\mathrm{SR_n}$) in function of the preferred stroke rate ($\mathrm{SR_P}$).

$$\mathrm{SR}_n = \frac{\mathrm{SR}}{\mathrm{SR}_P} \tag{3}$$

The swimming performance was assessed by the swimming speed (S, in m/s), as the time performed divided by the distance (ie, 25-m).

As mentioned in the introduction, leg kicking rate must be taken into consideration. In our study, as all the swimmers were requested to swim at their maximal speed, they always used a six-beat kick (as regularly observed in sprint[7]). The data were processed using MATLAB R2014a (The MathWorks, Inc).

2.4 | Statistical analysis

All the statistics were performed using R© software (version 3.3.0 GUI 1.68 Mavericks, R Foundation for Statistical Computing, 2016). Significance was set at $P < .05$. The normality of the distribution (Shapiro-Wilk test) and the homogeneity of the variance (Levene test) were checked before performing parametric tests. As these conditions were not met, Kruskal-Wallis tests (H) were performed to assess the gender effect and the stroke rate effect. Then, multiple comparisons for non-parametric tests were performed using the *nparcomp* package.[35] Following Vargha and Delaney,[36] effect size was assessed by epsilon-squared (ε^2), computed as follows:

$$\varepsilon^2 = \frac{SS_b - df_b\, MS_w}{SS_t} \tag{4}$$

SS_t is the total sum of the squares, SS_b is the sum of the squares between groups, SS_w is the sum of the squares within groups, df_b is the degrees of freedom between groups, and MS_w is the mean sum of the squares within groups (SS_w/df_w).

Epsilon-squared is considered small when <0.08, medium when $0.08 < \varepsilon^2 < 0.26$ and large when $\varepsilon^2 > 0.26$.[36] Last, individual regression modeling was performed to study the relationships (a) between the imposed stroke rate (normalized to the preferred stroke rate) and the achieved swimming speed, and (b) between the imposed stroke rate (normalized to the preferred stroke rate) and the achieved IdC. Linear ($y = c + bX$) and quadratic ($y = c + bX + aX^2$) models were tested with a significance level set at $P < .05$; then, the best model was selected based on the Akaike information criterion weighted ($\mathrm{AIC_w}$) and adjusted coefficient of determination (R^2_{adj}) following the Burnham and Anderson[47] procedures.

3 | RESULTS

3.1 | Task achievement: imposed vs performed stroke rate, stroke rate error, preferred and maximal stroke rate

Task achievement refers to how well the swimmers performed the stroke rate in comparison to the imposed stroke rate. Although the stroke rates were imposed in random order, the performed stroke rate increased significantly through the nine trials (for the whole sample, H(8) = 244.0; $P < .001$; $\varepsilon^2 = 0.75$, [0.69; 0.81]) (Figure 1). The maximal stroke rate was significantly higher than the preferred stroke rate (for women, respectively, 54.7 ± 3.3 and 49.2 ± 1.8 cycle/min; for men, respectively, 58.1 ± 5.4 and 53.5 ± 4.2 cycle/min), but it did not differ significantly from the performed stroke rate at P7 (for women, 54.2 ± 3.7 cycle/min; for men, 56.3 ± 2.6 cycle/min, whereas the imposed SR was 59 cycle/min) (Figure 1). For women, the performed stroke rate values ranged from −10 to + 10% of the preferred stroke rate, and the preferred stroke rate corresponded roughly to P4 (Figure 1). For men, the performed stroke rate values ranged from −25 to +5% of the preferred stroke rate, and the preferred stroke rate corresponded roughly to P5 (Figure 1).

Moreover, the women exhibited lower stroke rates than the men at P5, P6, P7, for the preferred and maximal stroke rate (H(1) = 9.5; $P < .001$; $\varepsilon^2 = 0.03$, [0.04; 0.07]; Figure 1). The women's lower stroke rates from P5 to P7 were related to their significantly higher error between the performed stroke rate and the imposed stroke rate compared with that observed in the men (female SR error: 4.6 ± 1.8%, male SR error: 3.2 ± 1.0%; H(1) = 7.39, $P = .006$; $\varepsilon^2 = 0.03$, [0.02; 0.09]).

Indeed, the stroke rate error for the women increased significantly through the seven imposed stroke rates (H(6) = 13.8, $P = .03$, $\varepsilon^2 = 0.13$, [0.06; 0.31]; Figure 2 shows that it was double the error at P5, P6 and P7 vs P1, P2, and P3), whereas a non-significant difference in stroke rate error was observed through the protocol for the men. Last, the error did not change significantly between the first and

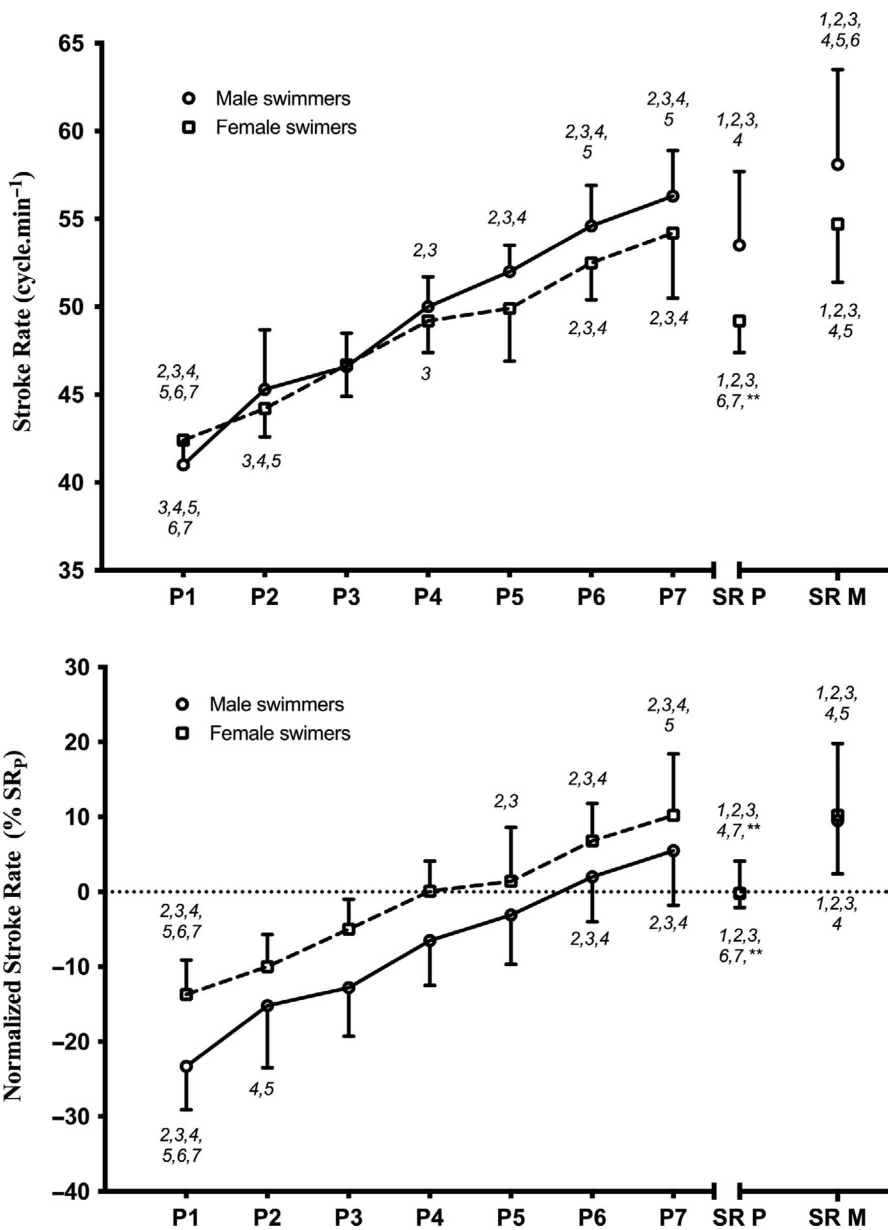


FIGURE 1 Upper panel: Evolution of the seven performed stroke rates (P1-P7), the preferred stroke rate (SR_P) and the maximal stroke rate (SR_M) in comparison to the imposed stroke rates. Lower panel: Evolution of the seven performed stroke rates (P1-P7) and maximal stroke rate (SR_M) in comparison to the preferred stroke rate (SR_P). Women: dashed line with squares and men: continuous line with circles; numbers correspond to the significant changes in comparison to a given trial; **: significant difference between SRP and SRM, with $P < .05$

second protocol sessions, suggesting that the dual task was performed both times with the same effectiveness.

3.2 | Changes in swimming speed according to the imposed stroke rate

For the whole population, the swimmers on average swam significantly faster when the stroke rate was increased ($H(8) = 21.83$, $P = .01$; $\varepsilon^2 = 0.07$, [0.04; 0.15]). However, an interaction between the gender effect and stroke rate effect showed that only men significantly increased their speed from 1.99 m/s at P1 to 2.09 m/s at P7, 2.10 m/s at preferred stroke rate, and 2.11 m/s at maximal stroke rate ($H(8) = 40.08$, $P = .0001$, $\varepsilon^2 = 0.21$, [0.14; 0.35]; Figure 3), whereas the women's speed did not change significantly (speed remained between 1.76 m/s at P1 and 1.84 m/s at maximal stroke rate). Moreover, a gender effect was observed, with men swimming significantly faster than women regardless of the imposed stroke rate ($H(1) = 226.39$, $P = .0001$; $\varepsilon^2 = 0.69$, [0.65; 0.72], Figure 3).

3.3 | Changes in index of coordination according to imposed stroke rate

For the whole population, the swimmers on average significantly increased their IdC when stroke rate increased (ie, IdC significantly changed from P1, P2, P3 to P5, P6, P7 SR_P and SR_M; $H(8) = 94.55$, $P = .0001$; $\varepsilon^2 = 0.29$, [0.23; 0.39], Figure 4), showing (a) a balanced coexistence of the three coordination modes at a stroke rate of 41 cycle/min and (b) a

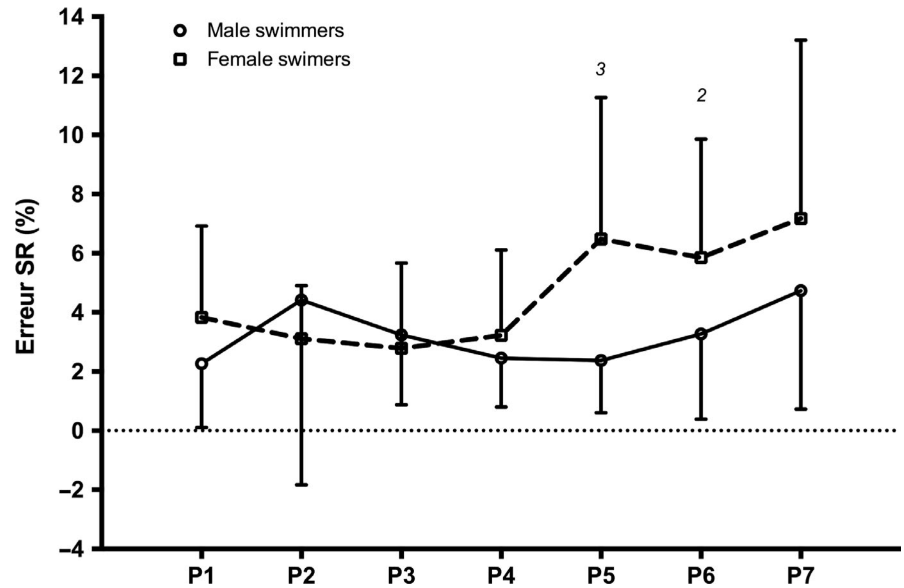


FIGURE 2 Evolution of stroke rate error for women: dashed line with squares and for men: continuous line with circles; numbers correspond to the significant changes in comparison to a given trial. with P < .05

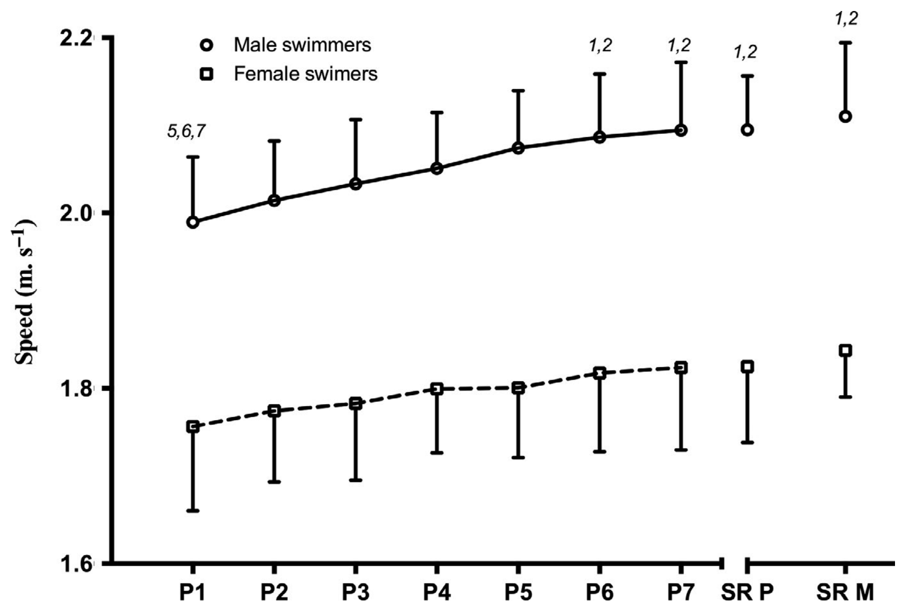


FIGURE 3 Changes in speed according to the imposed stroke rates (P1-P7), maximal stroke rate (SR_M) and preferred stroke rate (SR_P) for women: dashed line with squares and for men: continuous line with circle; numbers correspond to the significant changes in comparison to a given trial, with P < .05

75.7%-97.3% dominance of superposition coordination from a stroke rate of 44 cycle/min to maximal stroke rate (Table 1).

No significant gender effect occurred as both women ($H(8) = 49.39$, $P = .0001$; $\varepsilon^2 = 0.37$, [0.29; 0.54]) and men ($H(8) = 64.61$, $P = .0001$; $\varepsilon^2 = 0.28$, [0.21; 0.43]) increased their IdC with stroke rate (Figure 4), with values changing between 25.5% and 157.5% of the IdC at preferred stroke rate for women and between 4.8% and 133.4% of IdC at preferred stroke rate for men.

3.4 | Individual modeling of S-SRP and IdC-SRP

Speed-preferred stroke rate relationships were modeled by linear regression for eleven swimmers, by quadratic regression for five swimmers, and were non-significantly model-able for three swimmers (Figure 5).

IdC-preferred stroke rate relationships were modeled by linear regression for fourteen swimmers, by quadratic regression for four swimmers, and were non-significantly model-able for one swimmer (Figure 6).

4 | DISCUSSION

4.1 | Effect of stroke rate on swimming performance and arm coordination

Our findings indicated that for both men and women, the increase in stroke rate led to an increase in the IdC (Figure 4) and a switch from a mixed distribution of coordination modes

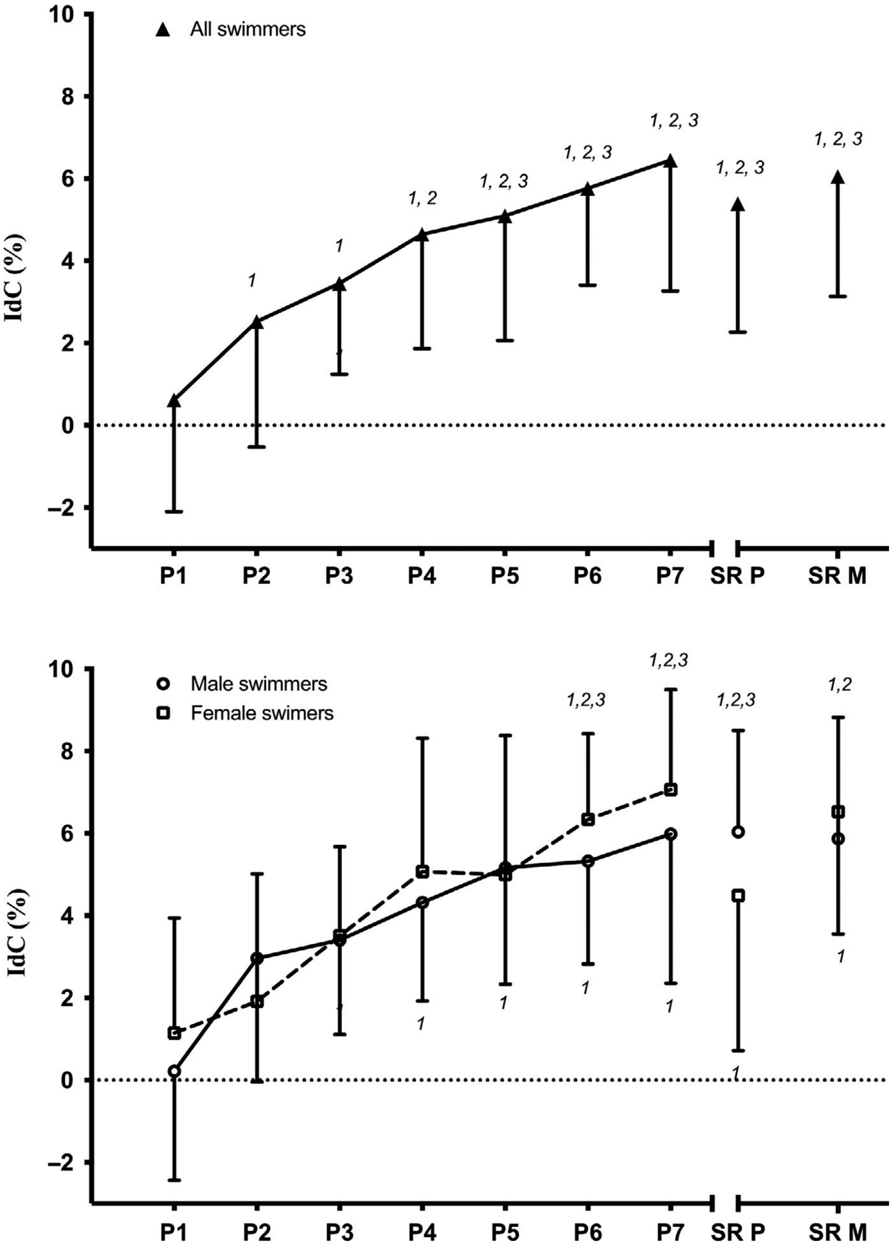


FIGURE 4 Changes in index of coordination (IdC) according to the imposed stroke rates (P1-P7), maximal stroke rate (SR_M) and preferred stroke rate (SR_P) for women: dashed line with squares and for men: continuous line with circles; numbers correspond to the significant changes in comparison to a given trial, with P < .05

to the high dominance of superposition (Table 1). Indeed, for the sample average at the lowest stroke rate (41 cycle/min), 27.8% exhibited catch-up coordination, 36.1% opposition, and 36.1% superposition, while at the highest imposed stroke rate (59 cycle/min), only 2.7% exhibited catch-up mode, 2.7% opposition, and 94.6% superposition (Table 1). Our results for elite swimmers agree with those of Potdevin et al[15] for regional and national swimmers, showing that superposition coordination may or not emerge through the interplay of external constraints summed up by the SR, and internal constraints (muscle strength, acceleration capacity). Indeed, previous studies on motor learning and motor control[20,22,37] have highlighted that a high level of constraint restricts the possibilities of motor solutions, whereas a low level of constraint allows a wider range of coexisting coordination modes.[38] Although 54.4% of the regional and 85.7% of the national swimmers still used catch-up coordination at 50 cycle/min,[15] our elite swimmers switched from catch-up to superposition at 47 cycle/min (Figure 4), which was a lower stroke rate than those achieved by the regional and national swimmers.[15] One explanation for the earlier switch in coordination modes of our elite swimmers resides in their higher swimming speeds, which were always near or above 2 m/s (Figure 3). Thus, our results confirmed previous findings showing a switch from catch-up to superposition mode at 47 <stroke rate <50 cycle/min and an associated speed of 1.8 m/s^2. These changes in arm coordination occurred concomitantly with a significant increase in swimming speed (from 1.99 ± 0.07 m/s at 41 cycle/min to 2.09 ± 0.08 m/s at 59 cycle/min) only for our elite male swimmers (Figure 3), who reached higher speeds than those observed by Potdevin et al[15] (from 1.44 ± 0.12 m/s at 40 cycle/min to 1.63 ± 0.12 m/s at 55 cycle/min).

TABLE 1 Percentage of occurrences of catch-up, opposition and superposition modes of coordination and stroke length (SL, in m) for the seven imposed stroke rates, the preferred stroke rate, and the maximal stroke rate

Gender	Coordination modes	P1 SR = 41	P2 SR = 44	P3 SR = 47	P4 SR = 50	P5 SR = 53	P6 SR = 56	P7 SR = 59	SR_P	SR_M
Women	catch-up	33.3	18.8	0.0	0.0	6.3	0.0	0.0	7.7	0.0
	opposition	20.0	12.5	0.0	0.0	0.0	0.0	0.0	7.7	0.0
	superposition	46.7	68.8	100.0	100.0	93.8	100.0	100.0	84.6	100.0
	SL Mean (SD)	2.48 (0.13)	2.41 (0.11)	2.29 (0.14)	2.20 (0.10)	2.17 (0.14)	2.08 (0.14)	2.03 (0.16)	2.23 (0.13)	2.03 (0.09)
Men	catch-up	23.8	9.5	0.0	0.0	4.5	4.5	4.5	4.5	0.0
	opposition	47.6	14.3	13.6	18.2	13.6	0.0	4.5	9.1	9.1
	superposition	28.6	76.2	86.4	81.8	81.8	95.5	90.9	86.4	90.9
	SL Mean (SD)	2.92 (0.15)	2.68 (0.20)	2.62 (0.14)	2.46 (0.10)	2.39 (0.11)	2.30 (0.12)	2.24 (0.12)	2.36 (0.19)	2.20 (0.21)
Whole population	catch-up	27.8	10.8	0.0	0.0	2.6	2.7	2.7	5.7	0.0
	opposition	36.1	13.5	8.1	10.8	7.9	0.0	2.7	8.6	7.7
	superposition	36.1	75.7	91.9	89.2	89.5	97.3	94.6	85.7	92.3
	SL Mean (SD)	2.73 (0.26)	2.56 (0.21)	2.48 (0.21)	2.35 (0.17)	2.30 (0.16)	2.21 (0.17)	2.15 (0.17)	2.31 (0.18)	2.15 (0.20)

Note:: P1-P7 correspond to the imposed stroke rate-imposed trials from 41 to 59 C/min.

The possible coordination mode from the Index of Coordination (IdC) is: catch-up (IdC < 0), opposition (IdC = 0), and superposition (IdC > 0). SR_P corresponds to the preferred stroke rate trial and SR_M to the maximal stroke rate trial. SL corresponds to the stroke length in m expressed as mean value and standard deviation SD for each population.

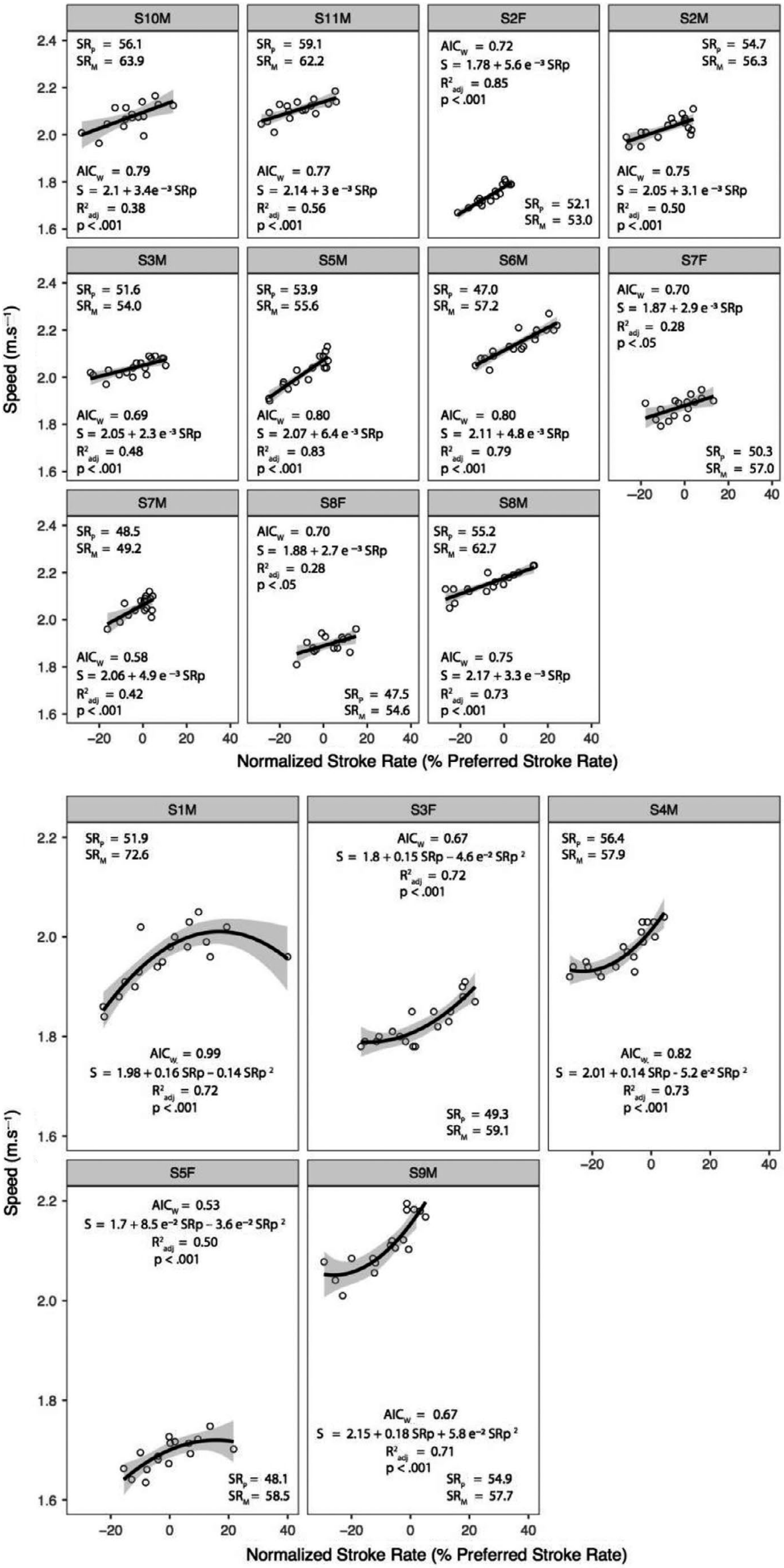
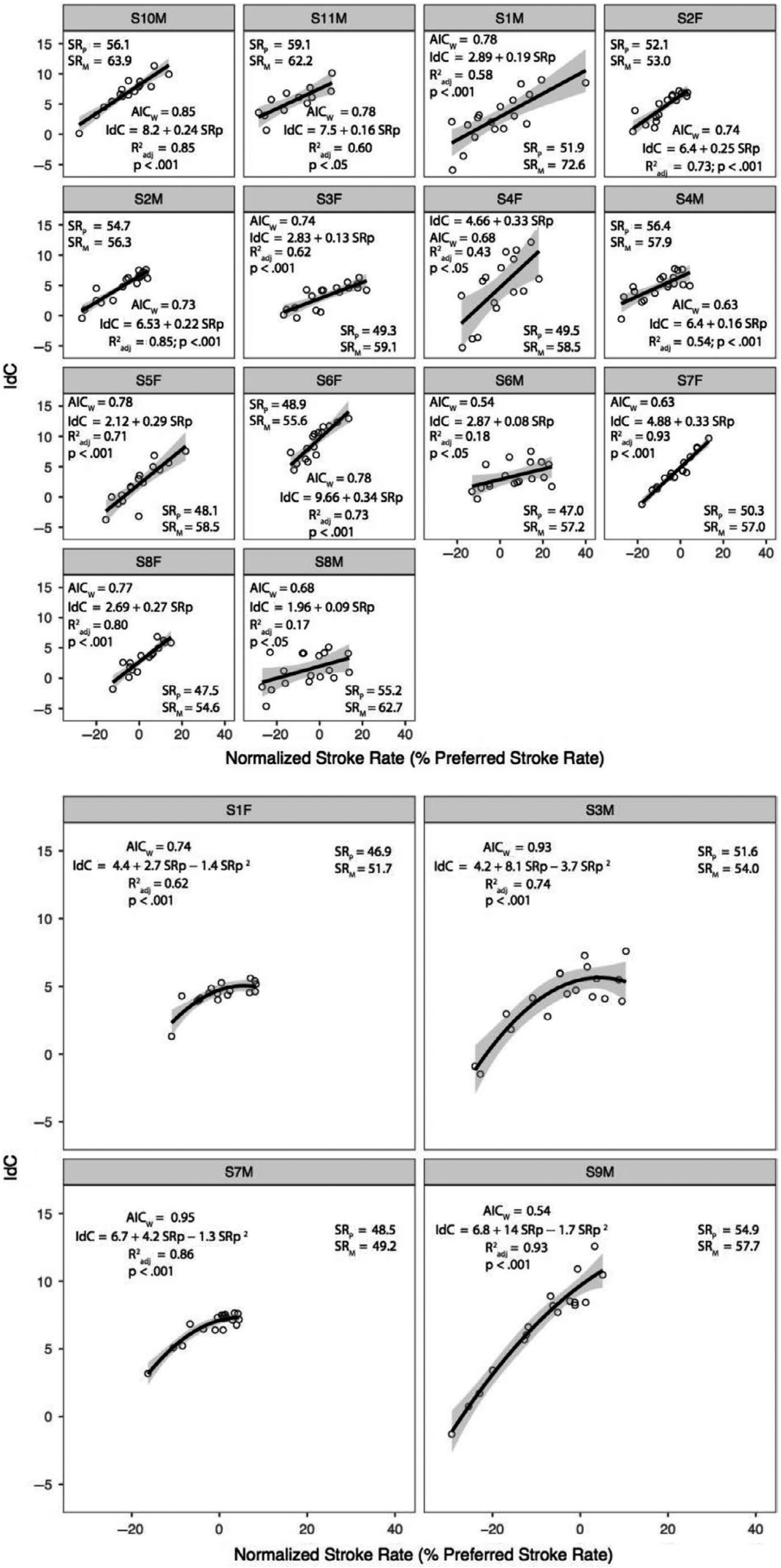


FIGURE 5 Individual regression modelling of speed (S) against the preferred stroke rate (SR_P). The confidence interval was plotted in the grey zone; R^2_{adj}: coefficient of determination; AIC_w: Akaike information criterion weight, maximal stroke rate (SR_M) and preferred stroke rate (SR_P) for each swimmer was indicated. The swimmer ID were indicated (S# and the gender M for male and F for female swimmer). At the top the linear models were plotted and at the bottom the quadratic models

FIGURE 6 Individual regression modelling of the index of coordination (IdC) against the preferred stroke rate (SR_P). The confidence interval was plotted in the grey zone; R^2_{adj}: coefficient of determination; AIC_w: Akaike information criterion weight, maximal stroke rate (SRM) and preferred stroke rate (SR_P) for each swimmer was indicated. The swimmer ID were indicated (S# and the gender M for male and F for female swimmer). At the top the linear models were plotted and at the bottom the quadratic models



4.2 | Effect of preferred stroke rate and gender on swimming performance and arm coordination

Although the increase in stroke rate generally led to an increase in the swimming speed and the IdC, these changes did not occur independently of the preferred stroke rate. Previous studies have reported that the metabolic cost and rating of perceived exertion are higher while walking at lower and higher stride frequency conditions than when walking at the preferred stride frequency condition both in water[39] and on dry land.[39,40] Holt[40] proposed that the preferred stride frequency of human walking can be explained by the interface of the resonance properties of the limbs as oscillators and the tendency of biological systems to self-optimize. Although swimming locomotion differs from walking in water and on land (and, consequently, gravity cannot be the only component of acceleration to compute resonant frequency), Figure 2 confirms that the stroke rate error (error between imposed and performed stroke rates) was the lowest at the preferred stroke rate. This finding suggests that the degree of constraint encountered by the neuromuscular system might be higher when swimming away from the preferred stroke rate (as already observed in walking and running at preferred stride frequency and at preferred speed[41,42]).

Moreover, the female swimmers had difficulties tolerating the imposed stroke rate above their preferred stroke rate, which might explain their narrower range of stroke rates (from −10 to +10% of the preferred stroke rate) and their non-significant changes in speed through the seven levels of stroke rate (Figure 2). Conversely, the men exhibited a wider range of stroke rates (from −25 to +5% of the preferred stroke rate) and, more importantly, their preferred stroke rate was higher (53.5 ± 4.2 cycle/min, corresponding to P5) than those of the women (49.2 ± 1.8 cycle/min, corresponding to P4) (Figure 1). Our results confirmed the findings of a pioneer study by Craig and Pendergast.[43] These authors attributed the women's lower stroke rate to their longer underwater phase, which they cannot compensate by shortening the aerial recovery phase of the arms. Indeed, Craig and Pendergast[43] showed that at maximal intensity, women have longer non-propulsive phases than men, suggesting their difficulty in achieving effective arm coordination. Although the IdC did not significantly change with gender in our study, it must be kept in mind that the women's arm coordination did not change above their preferred stroke rate (Figure 4), did not allow them to swim as fast as the men, and did not allow them to improve their speed when the imposed stroke rate was increased. Thus, their difficulties in matching the high values of the imposed stroke rates may be related to their lower strength and power output. In fact, comparing men and women at their maximal speed, Kolmogorov et al[44] observed higher active drag (D), but also higher mechanical power output (P_d) (knowing that $P_d = D \bullet v$ and men reach higher speeds than women) for men than for women, whereas K did not change significantly ($K = 0.5 \bullet Cd \bullet Ap \bullet \rho$, with Cd the drag coefficient, Ap the cross-sectional area, and ρ the water density). The highest speed reached at maximal intensity by the men could be explained by their higher power output, indicating that the anthropometric characteristics are not the only (or the most) discriminative gender parameters, as swimming technique (eg, arm coordination, see Seifert et al[5]) has an impact on active drag minimization and propulsive force generation.[44] In conclusion, women might not be able to reach stroke rates as high as those of men, which might be due to their lower strength and power output[44] and to their less effective arm coordination above their preferred stroke rate. Conversely, the "reserve" of power output in men might allow them to adapt their arm coordination more functionally in relation to stroke rate.

4.3 | Relationships between preferred and maximal stroke rate, swimming speed and arm coordination

For the difference between preferred (SR_P) and maximal (SR_M) stroke rates, seven of the sixteen swimmers for whom the regression models between S and SR were significant (Figure 5) had close SR_P and SR_M values (difference < 3 cycle/min) (S2F, S2M, S3M, S4M, S5M, S7M, and S9M), whereas the nine others exhibited a difference ≥3 cycle/min between SR_P and SR_M (S3F, S5F, S7F, S8F, S1M, S6M, S8M, S10M, and S11M) (Table 2). This difference of 3 cycle/min corresponds to the 5% SR variation regularly observed within and between laps when cycle-to-cycle analyses were performed during 100- and 200-m front crawl events in international competition, (see Hellard et al[8] and Simbaña-Escobar et al[10,11]).

The seven swimmers with a small difference (<3 cycle/min) between SR_M and SR_P showed low behavioral flexibility, which was logically associated with the highest stroke rate error and, for some of them, a plateau in their swimming speeds (Table 2). Conversely, the behavior of the nine swimmers with a large difference (≥3 cycle/min) between SR_M and SR_P can be related to high flexibility (Table 2). However, according to,[25] behavioral flexibility can be more or less "functional" regarding the performance outcome (ie, the swimming speed). In particular, the behavioral flexibility appeared "functional" for four swimmers who increased the swimming speed between SR_P and SR_M (S3F, S6M, S8M, S11M; Table 2). This group was composed of three top level front crawl sprinters and one French woman champion that they had a wide range of stroke rates to cope with race constraints (ie, fatigue, adversity, turn-in, and turn-out) and swam effectively out of their comfort zone (ie, away from their preferred stroke rate). Conversely, five other swimmers exhibited less functional stroke rate flexibility, as they did not

TABLE 2 Stroke rate flexibility around SR_p and concomitant changes in speed and arm coordination

Profile	Swimmer ID	SR_P (C/min)	SR_M (C/min)	SR difference ($C.min^{-1}$)	S at SR_P (m/s)	S at SR_M (m/s)	S difference (m/s)	IdC at SR_P	IdC at SR_M	IdC difference
Low flexibility of SR around SRp	S2F	52.1	53.0	0.9	1.80	1.80	0.01	7.0	6.5	−0.5
	S2M	54.7	56.3	1.6	2.07	2.07	0.00	7.0	6.7	−0.3
	S3M	51.6	54.0	2.4	2.05	2.09	0.04	6.0	4.8	−1.2
	S4M	56.4	57.9	1.5	2.02	2.04	0.02	6.3	6.3	0.0
	S5M	53.9	55.6	1.8	2.09	2.09	0.00	3.3	1.2	−2.2
	S7M	48.5	49.2	0.7	2.08	2.08	0.00	6.8	7.4	0.6
	S9M	54.9	57.7	2.8	2.18	2.17	-0.01	8.4	10.5	2.0
High flexibility of SR around SRp. but non-functional	S1M	51.9	72.6	20.7	2.04	1.99	-0.05	5.8	8.8	3.0
	S5F	48.1	58.5	10.5	1.72	1.70	-0.02	0.2	7.6	7.4
	S7F	50.3	57.0	6.7	1.91	1.90	-0.01	3.6	9.7	6.1
	S8F	47.5	54.6	7.1	1.94	1.96	0.03	2.4	5.9	3.5
	S10M	56.1	63.9	7.8	2.11	2.12	0.02	8.0	9.9	1.9
High and functional flexibility of SR around SRp	S3F	49.3	59.1	9.8	1.79	1.89	0.10	2.5	4.7	2.2
	S6M	47.0	57.2	10.2	2.12	2.24	0.12	3.8	4.3	0.5
	S8M	55.2	62.7	7.5	2.17	2.23	0.06	2.0	2.5	0.6
	S11M	59.1	62.2	3.2	2.13	2.19	0.05	7.6	7.1	−0.5

Note: Data are the stroke rate profile, the swimmer ID (F for female and M for male).

Performance measured S: speed (m/s), IdC: index of coordination, stroke rate: SR (C/min), and the difference of this values at SR_P the preferred stroke and SR_M maximal stroke rate.

Linear or quadratic regression between speed and SR_P did not fit the data ($P > .05$) for three swimmers: S1F. S4F and S6F.

improve their swimming speed between SR_P and SR_M (S5F, S7F, S8F, S1M, S10M; Table 2). This group of swimmers was composed of one front crawl mid-distance, one breaststroke, one backstroke, and two butterfly swimmers, who probably because they focused too much on reaching a high stroke rate in the SR_M condition without being able to generate high speed. Maybe because they were less specialized in front crawl these swimmers struggled with the dual task. Last, interestingly, swimmers exhibiting less functional SR flexibility were also those who further changed their arm coordination when swimming at SR_P and SR_M was compared, as the difference in IdC between the SR_M and SR_P conditions was mainly above 2% (Table 2). This suggests that the functional flexibility between the SR_M and SR_P conditions was not necessarily associated with a high-order parameter or deep changes (such as motor coordination).

In conclusion, although the increase in stroke rate led to an increase in swimming speed and the index of coordination, these changes did not occur independently of the preferred stroke rate. Indeed, the error between the imposed and performed stroke rates was the lowest at the preferred stroke rate, suggesting that the degree of constraint encountered by the neuromuscular system might be higher when swimming away from the preferred stroke rate. The female swimmers had difficulty respecting the imposed stroke rate above their preferred stroke rate, which might explain their lower range of stroke rates and their non-significant changes in speed through the protocol. Conversely, the men exhibited a wider range of stroke rates and, more importantly, their preferred stroke rate was higher than that of the women. Individual analysis revealed that some swimmers exhibited higher flexibility around their preferred stroke rate than others, as their difference between the preferred and maximal stroke rates was higher. This stroke rate flexibility appeared more functional in swimmers who reached a higher speed when swimming at maximal stroke rate than preferred stroke rate. As suggested by Termin and Pendergast[19] coach's need to use high-velocity training based in the stroke rate-speed relationship to enhance biomechanics and metabolism in the swimmers.

5 | PERSPECTIVES

Our study demonstrates the effect of swimming specialty (sprint vs long distance; for more details, see Bideault et al,[45] Seifert et al[46]), swimming technique (front, back, breast, butterfly strokes), and gender on stroke rate flexibility and suggest future research to confirm these aspects. As previously done by Termin and Pendergast,[19] our findings also suggest future research on stroke rate manipulation through intervention studies, using Aquapacer (tempo training) to prepare race strategy. For this purpose, we recommends (a) to identify the preferred stroke rate during competition, which corresponds to the stroke rate performed during the clean swimming part of the first lap; then (b) to check the stroke rate flexibility (ie, the range of stroke rates around the preferred stroke rate); and (c) to assess the functionality of this range by assessing whether cycles swum away from the preferred stroke rate (difference ≥ 3 cycles/min) are associated with a drop in swimming speed or not.

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CONFLICT OF INTERESTS

None declared.

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