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Case report

Stroke Rate and Arm Coordination Management in Swimming in A Double Paralympic Triathlete Champion

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Abstract

The 2024 Paris Paralympic triathlon required swimming with and against the current which requested to adapt stroke mechanics. To understand how a Paralympic triathlete champion might adapt his stroke mechanics under varying current conditions, this study aimed to 1) determine the range and optimal stroke rate (SR) and index of coordination (IdC); 2) examine the flexibility of SR, IdC and associated total energy expenditure. The para triathlete performed two front crawl tests: 10 times 25m incremented in swimming speed (S), from which S-SR and S-IdC relationships have been modelled to detect two regimes of functioning and the most effective SR; then, 6 times 50 m at the speed of the 800 m freestyle using 6 different SR conditions: spontaneous SR (SR_s), SR_s imposed by tempo trainer, SR_s+3, SR_s+6, SR_s-3 and SR_s-6 cycles. Total energy expenditure was computed from post-exercise oxygen uptake and blood lactate measurements. In test 1, the highest effective SR equals 44 cycle.min^{-1}, which corresponds to the preferred SR in 800 m freestyle competition. In test 2, the para triathlete struggled to perform the high SR conditions, which was associated to higher total energy expenditure; conversely, the para triathlete naturally decreased SR. It is advised to modulate SR around the preferred SR to optimise efficiency under varying current conditions.

Key words: Para swimming, kinematics, biomechanics, motor control, energetic.

Introduction

The swimming section of the 2024 Paris Olympics triathlon took place on a looped course in the Seine River, with one section went downstream while the other went upstream. Previous research has shown that active water circulation in a swimming pool significantly affects swimming performance depending on the current direction; in particular, swimming at 1.7 m·s^{-1} with a current of 0.1 m·s^{-1} would reduce the swimming time by ~1.6 s to cover 50 m, while swimming against the same current would increase the swimming time by ~1.8 s (Hinrichs and McLean, 1991). For the 2024 Paris Olympics triathlon, the flow rate of the Seine River was 220 m^3·s^{-1} for the paratriathlon. A rough estimation using an average depth of 4 to 5 m and an average river width of 100 m gives an expected flow rate of about 0.5 m·s^{-1} (Le et al., 2023). Therefore, the triathletes would have to adapt their motor organisation to cope with the current of the river, by adapting either low-order behavioural parameters such as spatial and temporal aspects of their swimming strokes, or high-order behavioural parameters such as motor coordination, or both (for more details, see Haddad et al., 2006). In this respect, as swimming speed (S, in m·s^{-1}) is the product of stroke length (SL, distance travelled by the body in one cycle and expressed in m·cycle^{-1}) and stroke rate (SR, number of arm movement performed in a given duration and expressed in cycle.min^{-1}), triathletes could adapt the ratio between SR and SL (i.e. change of low-order parameters) to achieve a given S. Moreover, they could also adapt coordination between arm movements and / or leg beat kick (i.e. change of high-order parameters). Chollet et al., (2000) proposed to assess coordination between arm movements by the index of coordination (IdC, in % of the cycle duration). The IdC quantifies the time between the end of the propulsive action of one arm and the beginning of the propulsive action of the other arm in front crawl (Chollet et al., 2000; Seifert and Carmigniani, 2021). The IdC value allows to distinguished the *opposition* (IdC = 0%), the *catch-up* (IdC < 0%) and the *superposition* (IdC > 0%) patterns of coordination (Chollet et al., 2000; Seifert and Carmigniani, 2021).

Swimming with the current of the river requires minimizing active drag due to body position and limb movements, notably by reducing SR and emphasizing forward glide in a streamlined position. Accordingly, previous studies have shown that long distance swimmers and triathletes used longer relative duration of arm glide than sprinters, resulting in catch-up pattern of arm coordination, with lower IdC found for long distance swimmers and triathletes than sprinters (Bideault et al., 2013; Millet et al., 2002). The relative duration of arm glide and catch-up pattern of arm coordination are amplified when wearing a wet suit (Hue et al., 2003), which is particularly relevant for open water swimmers and triathletes. Conversely, swimming against the current of the river could be biomechanically comparable to swimming in a flume, for which the

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water flow is generated artificially, requiring the swimmer to maintain position against the current (Guignard et al., 2017b). Previous experimental studies comparing swimming at similar S in a pool and in a flume have revealed higher SR, shorter relative duration of arm glide phase, and longer relative duration or arm pull and push phases when swimming in a flume (Espinosa et al., 2015; Guignard et al., 2017a; Wilson et al., 1998). Moreover, swimming in a flume revealed more in-phase coordination between hand and lower arm for the catch and glide and more in-phase coordination between hand and lower arm and between lower arm and upper arm couplings for the recovery phases, and lower flexibility of the coordination between arm movements (Guignard et al., 2020; Guignard et al., 2017a), suggesting that swimming against the current of the river might require to increase the SR and to adapt arm coordination pattern to overcome active drag.

Understanding the effects of the river current on propulsion generation requires examining how swimmers overcome active drag at varying swim paces. Recent findings have shown that overcoming active drag can be achieved through two regimes of functioning (Carmigniani et al., 2020): first, at low pace, i.e., low drag, swimmers minimise total energy expenditure, exhibiting a stable SL, a *catch-up* pattern of coordination and increase S mainly by increasing SR. In fact, at low pace, an optimal coordination corresponding to a catch-up pattern exists independently of the S. The swimmers maintained a constant IdC and varied their S by increasing their mean propulsive force. This is similar to the burst-and-coast swimming behaviour observed for certain fish such as cod or saithe (Videler and Weihs, 1982). If the fishes had a reduced drag during the gliding phase, they could consume less mechanical energy to maintain the same average S than in steady swimming. The extended arm during the glide phase in front-crawl appears to reduce body drag (Bulgakova and Makarenko, 1966). At higher swimming speed and drag levels, swimmers approaching their maximal force capacity, the propulsion time was minimal and did not vary (Carmigniani et al., 2020). To further increase swimming speed, the swimmers had to reduce their non-propulsive phases and the time between the propulsive phases of the two arms. Thus, the swimmers used a maximal force regime characterised by high increase of SR and of the continuity between propulsive actions, leading to a superposition pattern of coordination (Carmigniani et al., 2020; Seifert et al., 2007; Seifert and Carmigniani, 2021) above a swimming speed of 1.8 $m.s^{-1}$. Swimming speed in triathlon competitions corresponds to a low race pace referring to mid or long swimming distance such as 400 m, 800 m and 1500 m freestyle, for which a catch-up pattern of coordination was observed (Millet et al., 2002) as the arm glide phase was optimized to minimize drag like exhibited by long distance swimmers (McCabe and Sanders, 2012). This catch-up pattern of coordination would appear to be even more relevant when swimming with the current of the river during open water and triathlon competitions as swimmers attempt to optimise glide. However, when swimming against the current, the swimmers might switch to the second regime of functioning and would need to increase their SR, IdC and probably their leg kicking rate. SR represents a crucial low-order behavioural parameter determining S (Seifert et al., 2007; Simbaña-Escobar et al., 2020), and is tightly linked to the swimmer's physiological responses during performance. In fact, modulations in SR influence the distribution of energy between aerobic and anaerobic pathways (López-Belmonte et al., 2023; López-Belmonte et al., 2024b; Ohkuwa and Itoh, 1992). Moreover, although the legs less contribute than arms in front crawl propulsion (Deschodt et al., 1999; Gourgoulis et al., 2014), there is limited research on the contribution of the lower limbs propulsion (Dyer and Deans, 2017), which raises important questions about how leg amputation affects inter-limb coordination, SR, energy expenditure, efficiency of stroke mechanics and overall swimming performance in para athletes. Regarding efficiency of stroke mechanics, the jerk cost was recently proposed as a relevant indicator of stroke smoothness, with smoother stroke movement (i.e. lower jerk cost) observed in elite than in non-elite swimmers (Ganzevles et al., 2019) and in faster than in slower open water swimmers (Bouvet et al., 2023). In particular, Bouvet et al., (2023) found a significantly lower overall jerk cost value for faster swimmers suggesting their higher efficiency as well as lower impact of SR increase during race on stroke smoothness degradation. Therefore, examining the variation of jerk cost to different SR conditions around the preferred SR could inform on how the para triathlete adapts the motor coordination pattern and more globally his stroke mechanics, with practical applications when swimming in various current conditions. As mentioned previously, the swimming section of the para triathlon in Paris Paralympics required athletes to swim with the current on the outbound section and against the current on the return section of the Seine River. Therefore, the aim of this case study was to investigate the motor organisation of a two-time Paralympic triathlete champion with right lower leg amputation (class PTS4, which corresponds to moderate physical impairments including limb deficiencies, hypertonia, ataxia, athetosis, or impaired muscle power or range of movement) in order to support effective performance when swimming with and against the current of the Seine River for the Paris Paralympics. First, we assessed the SR-S relationship through an incremental test, and we modelled the two regimes of functioning to detect the most effective SR and arm coordination pattern. The most effective SR would allow the highest stroke index, i.e. resulting from the product of S and SL. Second, although we did not manipulate the water flow, we examined the adaptability of SR and arm coordination as well as the associated total energy expenditure and jerk cost to explore whether the para triathlete could adapt his motor organisation in a way that would allow him to cope efficiently with the current to swim in the Seine River. We hypothesised that high flexibility of SR and arm coordination could support adaptive performance in future races or training situations involving variable current conditions.

Methods

Participant

An elite male para triathlete (class PTS4) with a right lower leg amputation, voluntarily participated in this study and provided written informed consent. The para triathlete is an 8-time European champion, 8-time World champion, 2-time Paralympic gold medallist (in Tokyo 2021 and Paris 2024). All procedures were performed according to the Declaration of Helsinki and approved by the National Ethics Committee (national agreement number: 2021-A01186-35) and was registered in https://www.clinicaltrials.gov with the ID NCT05011591.

Protocol

The para triathlete performed a self-selected warm-up in the water during at least 20 min. Thereafter, the range of his repertoire of SR and arm coordination was assessed through 10 times 25 m front crawl trials at incrementally increased self-selected speed (S), from the slowest to his maximal speed. This test aimed to detect the two regimes of functioning and the most effective SR (i.e. associated to the highest stroke index) in a non-fatigued state (Carmigniani et al., 2020). Speed was self-paced, and the total increase in S across trials was required to be at least 40 %, corresponding to an approximate 4 - 5 % increase per trial. The para triathlete was able to match the required target time for every trials. Finally, a 3 mins rest was allowed between each trial (as already done in previous studies, e.g., Carmigniani et al., 2020; Seifert et al., 2007).

The para triathlete returned on a separate occasion to perform a second test to examine the adaptability of his SR and arm coordination, in order to assess his potential to adapt motor organisation to swimming with and against the current of the Seine River. This test corresponded to swim 6 times 50 m front crawl in outdoor 50 m pool close to the S of his personal best time on 800 m freestyle (i.e., 9 min 28 s in March 2024, performed during a test event in a 50 m pool, corresponding to an average speed of 1.41 m.s^{-1}) with a 8 mins rest between each trial. The first 50 m was performed at spontaneous SR without any instruction (SR_s), the second 50m was performed at spontaneous SR imposed by a tempo trainer (SR_i), then the next four 50 m were spontaneous SR -6 cycles (SR_{s-6}), -3 cycles (SR_{s-3}), +3 cycles (SR_{s+3}), +6 cycles (SR_{s+6}). Each SR condition was imposed by a pacing device, i.e., an auditory metronome (Aquapacer Tempo Trainer Pro® Finis, Inc, California, USA) placed under the cap (as already done in previous studies; Mclean et al., 2010; Simbaña-Escobar et al., 2020). As the para triathlete was tasked with simultaneously maintaining the imposed SR and swimming at maximal effort, he was instructed to prioritise maintaining the imposed SR while aiming to swim at the pace of his 800 m personal best. The speed of the 800 m freestyle was chosen because the swimming section of the PTS4 class Para triathlon in Paris Paralympics 2024 corresponded to 750 m. Before starting the protocol, the para triathlete had a familiarization session and trained with the pacing device. Both tests were performed with an in-water start, initiated swimming within 5 m of the wall and with breath holding during the last 25 m to avoid potential asymmetric motor coordination due to unilateral breathing pattern (Seifert et al., 2024).

Data collection

The para triathlete was equipped during the whole test with three waterproof inertial measurement units (IMUs) (Wavetrack, Cometa, Milan, Italy) positioned on the right and left lower arms, and on the sacrum, recorded kinematic data continuously throughout the tests (Guignard et al., 2017a; Regaieg et al., 2023; Seifert et al., 2024). Calibration of IMUs was made before recording as previously done (Guignard et al., 2017a; Regaieg et al., 2023; Seifert et al., 2024).

Moreover, an above-water lateral video camera (GoPro8, 50 Hz) recorded over a 10 m distance (from 10 m to 20 m) using the swimmer's head as the marker (Chollet et al., 2000; Seifert et al., 2007). Time over this 10 m distance was used to compute S. The synchronisation between the video camera and IMUs systems was performed by rapid and dynamic strikes on the IMU positioned on the left lower arm and was recorded by the camera prior each trial (Guignard et al., 2017a; Regaieg et al., 2023; Seifert et al., 2024).

To quantify energy expenditure, pulmonary gas exchange was measured 1 min before and 3 min after each 50 m repetition (Metamax 3B, Cortex, Leipzig, Germany) (DiMenna et al., 2010; Robergs, 2014). Heart rate (HR) was continuously measured throughout the entire session (warm-up, exercise, and inter-repetition recovery following each exercise bout) using a beat-by-beat monitor (Forerunner 945® with HRM-Swim™ belt, Garmin, Olathe, USA) (Rodríguez et al., 2017). Ectopic beats were removed, and heart rate was averaged at 1-second intervals. Blood samples (0.3 µL) were obtained from the para triathlete's finger before and at 1, 3, 5, and 7 min after each 50-meter repetition and were immediately analysed for lactate evaluation [La] (Lactate Pro 2, Arkray, Kyoto, Japan) (Massini et al., 2022).

Data analysis

The cycle duration (T, in seconds) was defined as the time between two consecutive water entries of the same hand (obtained as in Regaieg et al., 2023) within this 10 m distance was computed from the corresponding lower arm IMU and averaged to obtain the SR (SR = 1/T•60, in cycle.min^{-1}) and the SL (SL = S/SR•60, in m).

Regarding arm coordination, the hand entry, the catch, the moment at which hand is passing at the vertical of the shoulder (i.e., beginning of push phase according to Chollet et al., 2000) on the sagittal plane and the water hand exit was detected from angular velocity signal of the gyroscope's IMU following exactly the procedure of previous studies (Regaieg et al., 2023; Seifert et al., 2024; Simbaña - Escobar et al., 2020). Those key points allowed to compute the relative duration of the propulsive phases (i.e. pull and push) and non-propulsive phases (i.e. hand entry, catch and recovery), to finally quantify the IdC (Chollet et al., 2000; Regaieg et al., 2023; Seifert et al., 2024).

Regarding the efficiency and smoothness of stroke mechanics, the jerk cost was computed from acceleration data collected by the IMU located at the sacrum. From the raw acceleration data, cycle beginning and end were identified with a zero-crossing on the mediolateral acceleration filtered with a second-order Butterworth band-pass filter between 0.1 and 1 Hz (Ganzevles et al., 2019). Then, jerk cost was computed as the average of the squared jerk signal coming from the derivative of the acceleration Euclidean norm following a second-order Butterworth band-pass filter between 0.1 and 5 Hz (Ganzevles et al., 2019). A low jerk cost refers to a smooth stroke mechanics whereas a high jerk cost indicates a jerky stroke mechanics.

Data from the 10 times 25 m were modelled to determine two regimes of functioning on one hand by the relationships between S, SR and SL and on another hand by the relationships between S and IdC using linear regressions (Figure 1). The first regime is modelled as $S = (S_c/SR_c)\bullet SR$ where $S_c/SR_c = SL_c$ (dotted line in Figure 1). According to Carmigniani et al. (2020), the transition point ($_c$) between the two regimes was identified by a square root model ($S = \sqrt{(SI_{max}\bullet SR)}$ passing by SI_{max} (solid line curve in Figure 1, left panel). The first regime corresponds to a constant coordination, which is equivalent in its formulation to a constant SL. In this regime, IdC is maintained constant while increase in S results from the increase in generated force. Once maximum force is reached, a transition occurs into a maximum force regime, in which the stroke index (SI) is maximum ($SI_{max} = S_c\bullet SL_c$). To further increase S, the duration of the glide and recovery phases is reduced. The para triathlete might have difficulties to maintain his maximum SI as his SR increases. To outline this difference to the optimal model, the second regime was modelled as $S = a\bullet(SR - SR_c) + S_c$ (hatched line in Figure 1). Finally, the potential gain of S was estimated by computing the area between the optimal model ($S = \sqrt{(SI_{max}\bullet SR)}$) and the current model of the second regime ($S = a\bullet(SR - SR_c) + S_c$) (taking the range between the maximal SR and the theoretical SR_c). All those analyses have been performed using MATLAB R2020b (The MathWorks, Inc. Natick, MA, USA).

Before and after swimming, oxygen uptake ($\dot{V}O_2$) and HR data were time-aligned during recovery measurements, 1 s interpolated, and plotted against time (Rodríguez et al., 2017). Then, all the values were averaged over 20 s. The values of $\dot{V}O_2$ at the end of each swimming exercise (EE_$\dot{V}O_2$) were computed by mathematical model based on synchronized postexercise $\dot{V}O_2$ and HR values recorded during the first 20 s of the recovery period and HR measurements during the last 20 s of each swimming trial (Monteiro et al., 2020). The aerobic part of swimming was equal to the $\dot{V}O_2$ assessed by backward extrapolation of the first 20s of recovery value (EE_$\dot{V}O_2$). Anaerobic glycolytic energy was estimated using the higher [La] value measured during the seven minutes of inter-recovery repetition. [La] values were converted to oxygen equivalent values as 3 mLO_2 kg^{-1} of bodyweight per mmol of blood lactate (O_2 eq. [La]) (di Prampero and Ferretti, 1999). As the swimming speed is considerably lower than 200 m front crawl performance speed, anaerobic alactic energy sources were to be neglected (Fernandes et al., 2006). Considering that the respiratory quotient (RQ) at the swimming speed of the 800 m trial was below 0.96, the values of aerobic (EE_$\dot{V}O_2$) and anaerobic (O_2 eq. [La]) contributions were multiplied by the energy equivalent of $1LO_2$, i.e. 20.9 kJ (di Prampero, 1986). Thus, the total energy expenditure (E_{total}) was calculated as the product of the sum of energy equivalent of EE_$\dot{V}O_2$ and O_2 eq. [La] (Komar et al., 2012; Massini et al., 2022): $E_{total} = (EE\_\dot{V}O_2 + O_2 \text{ eq. [La]})\bullet 20.9kJ.LO_2^{-1}$

Pearson correlation tests between motor organisation (IdC), smoothness and efficiency of stroke mechanics (SI and jerk cost) and total energy expenditure (E_{total}) were computed with significant p-value set at < 0.05.

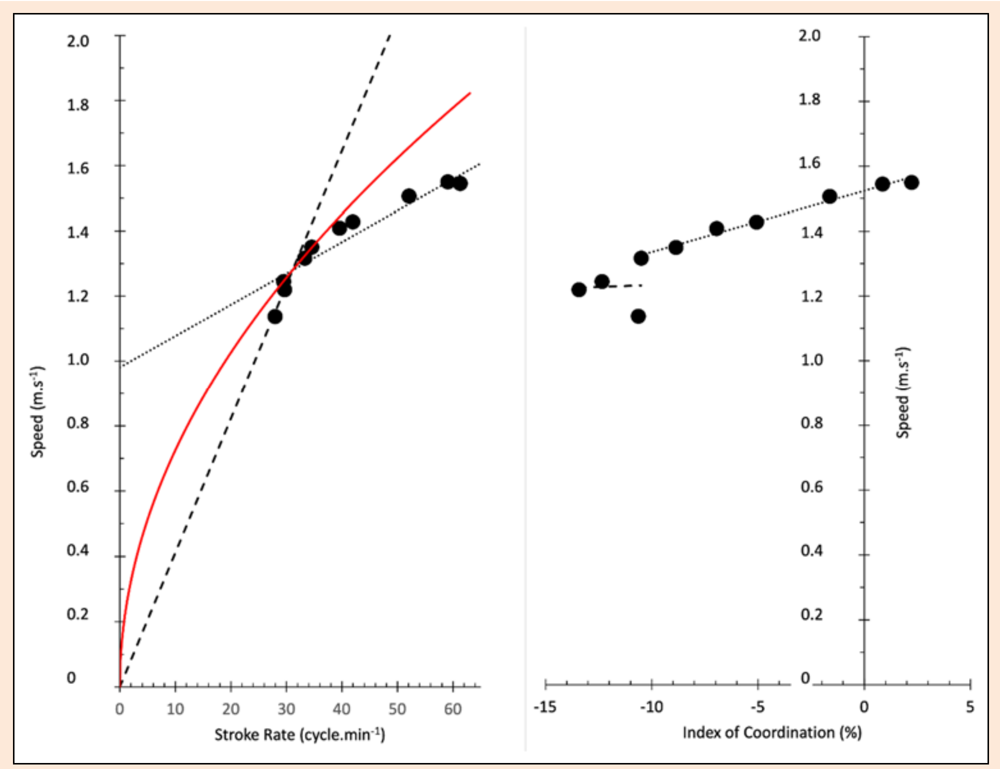

Figure 1. Modelling of the two regimes of functioning for the relationships between S and SR (left panel), and between S and IdC (right panel).

Results

During the 10 times 25 m incremental test, the para triathlete exhibited a S range of 40% (from 1.1 to 1.55 $m \cdot s^{-1}$), a SR range of 120% (from 27.5 to 61.3 $cycle.min^{-1}$), a SL range of 67% (from 1.51 to 2.44 m), a SI range of 35% (from 2.34 to 3.16 $m^2 \cdot s^{-1}$) and a IdC range of 116% (from -13.4 to 2.2 % of the cycle duration) (Figure 1). The transition point ($_c$) at which the para triathlete switched between the two regimes occurred for S_c = 1.28 $m \cdot s^{-1}$, SR_c = 31.1 $cycle \cdot min^{-1}$, SL_c = 2.47 m and SI_{max} = 3.16 $m^2 \cdot s^{-1}$ (Figure 1) and was associated to an IdC of -10%.

SR started dropping from the optimal model (i.e., the red curve) at 44 $cycle \cdot min^{-1}$. When computing the area between the optimal model ($S = \sqrt{(SI_{max} \bullet SR)}$) and the current model of the second regime ($S = a \bullet (SR - SR_c) + S_c$), a potential gain of S of 0.13 $m \cdot s^{-1}$ was estimated.

In the 6 times 50 m swam at the S of his personal best time on 800 m freestyle, the para triathlete exhibited a SR_s of 50 $cycle \cdot min^{-1}$ and demonstrated better accuracy to respect lower SR (i.e. SR_{s-6} and SR_{s-3}) than higher SR (i.e. SR_{s+3} and SR_{s+6}) conditions, with S within a range of 1.40 to 1.46 $m \cdot s^{-1}$ (Figure 2). Although the para triathlete was right leg amputee, he performed 3 left leg beat-kick and 3 right thigh beat-kick, which corresponds to 6 leg-beat kick, regardless the SR conditions. IdC ranged from -4 to 4%, SI ranged from 2.24 to 2.84 $m^2 \cdot s^{-1}$, jerk cost ranged from 1.39 $x10^3$ $m^2 \cdot s^{-5}$ to 1.71 $x10^3$ $m^2 \cdot s^{-5}$ and E_{total} ranged from 93.65 to 109.64 kJ (Figure 2, Figure 3 and Figure 4), depending on the repetition and the SR targets. The highest value of SI (2.84 $m^2 \cdot s^{-1}$) and the lowest values of IdC (-4.26 %), jerk cost (1.39 $x10^3$ $m^2 \cdot s^{-5}$), E_{total} (93.65 kJ) and $EE\_\dot{V}O_2$ (68.85 kJ or 73.5 % of E_{total}) were observed during the SR_{s-6} condition (Figure 2, Figure 3 ve Figure 4). Conversely, lower value of SI and higher values of IdC, jerk cost and E_{total} were observed when spontaneous SR was imposed (SR_i) and in high SR conditions (i.e. SR_{s+3} and SR_{s+6}) (Figure 2, Figure 3 and Figure 4). Significant correlations between SI (-0.57), jerk cost (0.60) E_{total} (0.77) and IdC were found ($p < 0.05$). Significant correlations between SI (-0.86), jerk cost (0.84) and E_{total} were found ($p < 0.05$). Finally, significant correlation between SI and jerk cost (-0.79) was found ($p < 0.05$).

The O_2 eq. [La] value accounted for 26.5% of E_{total}, representing the highest anaerobic contribution, both in percentage of E_{total} and in absolute value (24.83 kJ) (Figure 4). The highest E_{total} values were observed for the SR_{s+3} (109.64 kJ) followed by SR_{s+6} conditions (107.34 kJ). The $EE\_\dot{V}O_2$ also reached its highest values in SR_{s+3} (84.87 kJ) and SR_{s+6} conditions (84.58 kJ). A total of 78.8% of E_{total} was derived from $EE\_\dot{V}O_2$, while 21.2% originated from O_2 eq. [La]. As such, the contributions of aerobic and anaerobic metabolism, when expressed as percentages of total energy expenditure, were the highest and lowest, respectively, in the SR_{S+6} condition. Expressed in absolute value, O_2 eq. [La] reached its nadir after SR_{s-3} trial. Thus, swimming at the SR_s incurred a higher E_{total} compared to swimming at a lower SR, yet remained less costly than swimming at a higher SR, primarily due to difference in $EE\_\dot{V}O_2$.

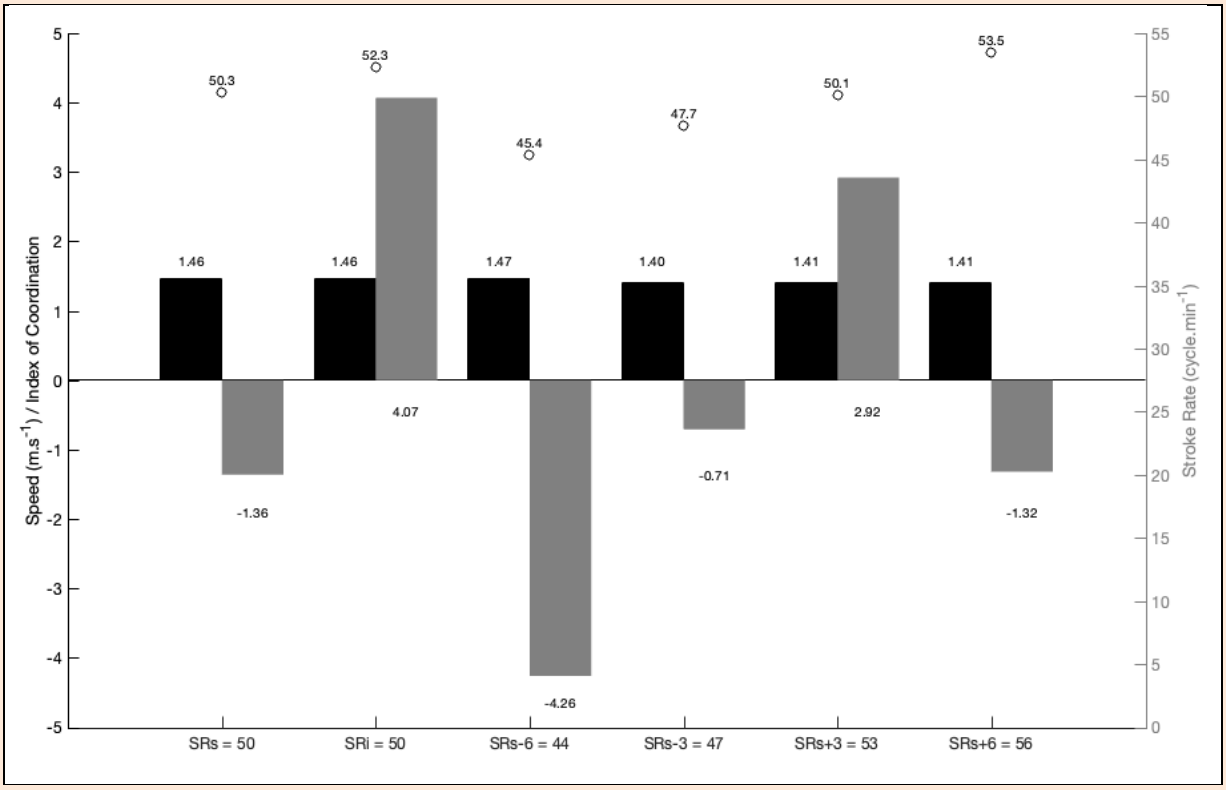

Figure 2. Current stroke rate, speed and index of coordination performed in the 6 stroke rate conditions: spontaneous SR without any instruction (SRs) and imposed spontaneous SR (SR_i), spontaneous SR-6 cycles (SR_{s-6}), -3 cycles (SR_{s-3}), +3 cycles (SR_{s+3}), +6 cycles (SR_{s+6}).

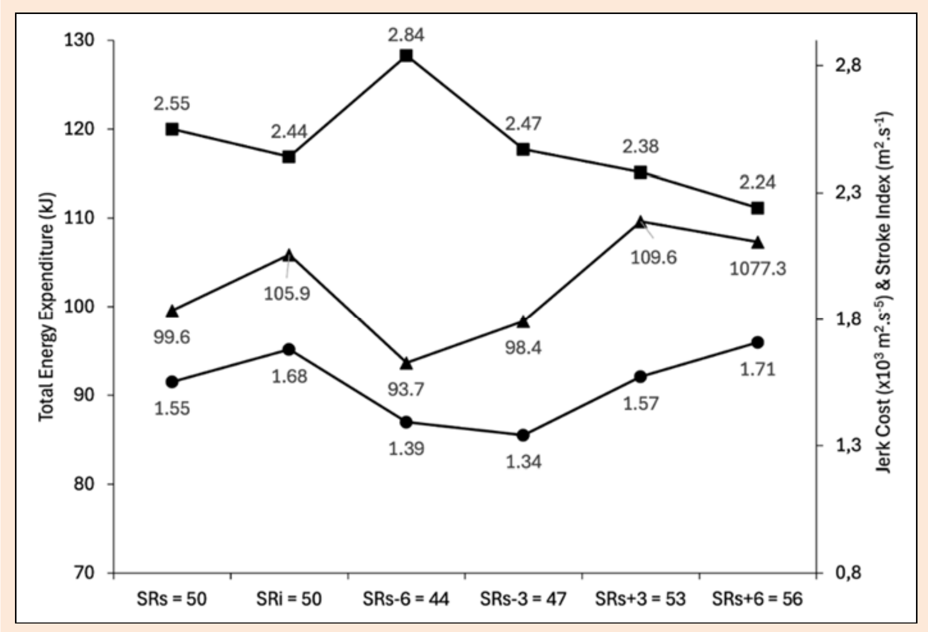

Figure 3. **Total energy expenditure (black dot, in kJ), Stroke Index (black square, in $m^2 \cdot s^{-1}$) and Jerk Cost (black triangle, x103 $m^2 \cdot s^{-5}$) in the 6 stroke rate conditions: spontaneous SR without any instruction (SRs) and imposed spontaneous SR (SRi), spontaneous SR-6 cycles (SR_{s-6}), -3 cycles (SR_{s-3}), +3 cycles (SR_{s+3}), +6 cycles (SR_{s+6}).**

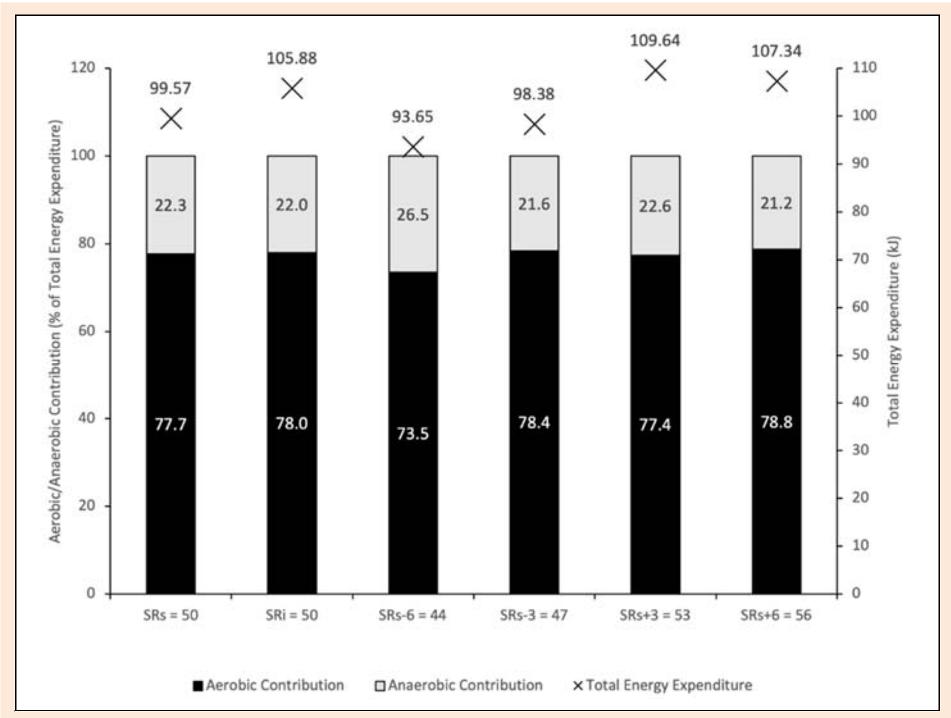

Figure 4. **Total energy expenditure (black dot, in kJ) and percentage of aerobic (in grey) and of anaerobic (in white) contribution (in % of total energy expenditure).**

Discussion

The aim of this case study was twofold: modelling motor organisation and assessing its flexibility under energy constraints for a Para triathlon champion. The results of first regime confirmed our hypothesis that a constant SL of 2.47 m and a catch-up pattern of arm coordination (quite constant IdC within -13 and -10% of the cycle duration) reflect upper limbs glide to minimize drag, and consequently to reach a high SI of 3.16 $m^2 \cdot s^{-1}$. An IdC of -13 to -10% was already observed in non-disabled elite swimmers at low pace and reflect upper limbs glide (Bideault et al., 2013; Seifert et al., 2007). Assuming that swimming with the current affords more glide than swimming in a pool (i.e. in a quasi-steady state water flow; see Guignard et al., 2017b for more details), the para triathlete might be able to adapt his arm coordination toward a catch-up coordination pattern when swimming with the current as exhibited at low pace in a pool. The high and constant SI at low pace suggests that the para triathlete could effectively adapt his SR and his arm coordination pattern to swim with the current.

When examining at the second regime of functioning, as hypothesised, the para triathlete had difficulties to maintain his maximum SI as his SR increases. Indeed, a non-proportional increase between SR and S could be observed during the second regime as SR increased by 197% (from 31.1 to 61.3 cycle·min^{-1}) while S increased only by 121% (from 1.28 to 1.55 m·s^{-1}), which explained that his SI decreased by 74% (from 3.16 to 2.34 m^{2}·s^{-1}). As a result, at maximal speed, he swam at a SR of 61.3 cycle·min^{-1} and IdC until 2.2% (i.e., a superposition pattern of arm coordination), which allowed him to reach a speed of 1.55 m·s^{-1} whereas elite non-disabled swimming sprinters usually reach at least 2 m·s^{-1} with such behaviour (Carmigniani et al., 2020; Seifert et al., 2007; Seifert and Carmigniani, 2021). As a para triathlete who never competed in sprint races, it could be acknowledged that he reached such high value as maximal SR. Interestingly, SR started dropping from the optimal model (i.e., the solid line curve in Figure 1, left panel) at a 44 cycle·min^{-1} value, and at a S of 1.43 m·s^{-1}, which corresponds to his preferred SR and S used in 800 m freestyle competition. When computing the area between the optimal model and the current model of the second regime, a potential gain of S of 0.13 m·s^{-1} was estimated (taking the range between the maximal SR and the theoretical SR$_c$). This potential gain remains theoretical as maintaining SI at high S is difficult or even impossible. However, SI was found to be the main predictor of open water swimming performance in triathletes (López-Belmonte et al., 2024a). Therefore, although triathletes and long-distance swimmers generally do not aim to increase SR beyond their preferred range, maintaining SI while increasing SR remains important when sprinting. In the context of the Paralympics in Paris within which it was requested to swim 750 m (*vs.* 1500 m for non-disabled triathletes) with and against the current of the Seine River, the question was to examine how this para triathlete can adapt his spontaneous SR near the 800 m preferred pace without compromising S and without additional total energy expenditure.

The findings of the second test (6 times 50 m swam at the personal best time of 800 m freestyle) exhibited a spontaneous SR of 50 cycle·min^{-1}, which was higher than the 44 cycle·min^{-1} usually observed in this para triathlete during his previous competitions. Therefore, the para triathlete logically struggled to respect this SR of 50 cycle·min^{-1} when imposed by the tempo trainer (as a gap of +2.3 cycle.min^{-1} occurred despite the familiarization before the test) and exhibited higher total energy expenditure and jerk cost. Spontaneous SR was requested for the first 50 m trial instead of imposing the preferred SR of 44 cycle.min^{-1} to avoid that any instructions can generate additional attentional cost. The fact that triathletes (as well as long distance swimmers and open water swimmers) are not trained mainly in sprint (i.e. high S and high SR training) might explain why the para triathlete struggled to respect high SR, and when he was able to reach high SR, he exhibited higher energy expenditure and lower efficiency (i.e. lower SL, lower SI and higher jerk cost). This interpretation is supported by a study of Millet et al., (2002) showing that during 6 times 25m at incrementally increased self-selected S, from the slowest to his maximal S, elite triathletes achieved lower S than elite swimmers, mainly because triathletes exhibited shorter propulsive phases and generated lower SL. Moreover, difficulties to match the imposed SR, associated to higher total energy expenditure and jerk cost, also occurred for higher SR conditions (i.e. SR$_{s+3}$ and SR$_{s+6}$, respectively 53 and 56 cycle·min^{-1}) as already observed (Simbaña-Escobar et al., 2020). Nonetheless, the present findings reinforce the critical role of SR in determining the overall energetic cost and stroke mechanics smoothness and efficiency (i.e. jerk cost) of front-crawl swimming. Indeed, in open water competition, Bouvet et al., (2023) showed that the best performers used lower jerk cost to achieve the same speed in the peloton, which allowed them to prepare for a fast end-spurt during the last quarter of the race, notably by increasing SR from 38-39 to 41 cycle·min^{-1}. In our study, modulations of SR were shown to influence not only the total energy expenditure but also the balance between aerobic and anaerobic metabolic contributions, and the jerk cost.

Swimming at SR$_s$ and SR$_i$ incurs a higher energy cost and jerk cost compared to swimming at a lower SR, yet remains less costly than swimming at a higher SR, primarily due to variations in aerobic demand. Specifically, swimming at higher SR (SR$_{s+6}$ = 53 *vs.* SR$_{s-6}$ = 44 cycle.min^{-1}) increased the aerobic demand by 5.3% and total energy expenditure by 13.69 kJ (Figure 4), aligning with previous work by López-Belmonte et al., (2023), who identified SI responses (average value of 2.50 ± 0.34 m^{2}.s^{-1}) as a key determinant of 1500 m performance in triathletes. Although the work of López-Belmonte et al., (2023) concerned the 1500 m race distance (*vs.* 750 m race distance at the Paralympics), the moderate negative correlations previously observed between aerobic contribution (r = -0.47), total energy expenditure (r = -0.46) and S suggest that higher values in these metrics may be indicative of lower performance. Moreover, the positive relationship found with the anaerobic contribution (r = 0.30), SI (r = 0.72), SL (r = 0.59) and S (López-Belmonte et al., 2023) are consistent with the idea that motor organisation (low- and high-order behavioural parameters) and anaerobic/aerobic ratio in metabolic contribution play a significant role in performance. Physiologically, these results are supported by the findings of Ohkuwa and Itoh (1992), who showed that full-stroke crawl swimming results in significantly higher blood lactate concentration compared to isolated arm or leg actions, underscoring the energetic load associated with coordinated stroke execution. The increase in blood lactate levels with full-body engagement suggests that SR modulation must account for the swimmer's metabolic capacity to avoid premature fatigue. In this context, selecting a submaximal, yet effective SR may provide a more favourable energy profile, minimizing anaerobic reliance and lower jerk cost (smoother and more efficient stroke mechanics) while preserving motor organisation. Although it was assumed that a lower jerk cost reflects a lower energetic cost (Bouvet et al., 2023; Hogan and Sternad, 2009; Hreljac and Martin, 1993), no experimental studies checked the correlation between those two metrics, and the potential effect of SR modulation on those metrics. Overall, our results highlight the tight correlation between motor organisation, total energy expenditure, and smoothness and efficiency of stroke mechanics, emphasizing the need for individualized SR strategies based on both the targeted S and metabolic thresholds.

Moreover, differences in SR strategies are accentuated by environmental factors. López-Belmonte et al., (2024a, 2024b) reported that elite triathletes exhibit distinct SR patterns in open water compared to pool conditions, likely reflecting adaptations to pacing and energetic constraints. More precisely, lower SL and SI and higher SR were obtained in open water compared with pool swimming, while no differences were found in the main physiological variables (López-Belmonte et al., 2024b). Previous research performed in flume examining the effect of SR modulations ($SR_{s-20\%}$, $SR_{s-10\%}$, $SR_{s+10\%}$, $SR_{s+20\%}$) on physiological parameters on non-disabled swimmers have shown contrasted results probably because of a very different experimental setting (Mclean et al., 2010); in particular, swimming speed was set at the low value of 1 $m.s^{-1}$ for which a low SR_s of 30 $cycle·min^{-1}$ emerged. The findings exhibited significant higher mean oxygen uptake, mean heart rate and mean leg kicking rate when the swimmers performed lower SR ($SR_{s-20\%}$, $SR_{s-10\%}$) than the SR_s (Mclean et al., 2010). Reducing the SR_s by 10 and 20% requested to swim respectively at 24 and 27 $cycle.min^{-1}$, which led the participants to compensate by higher leg kicking rate, explaining the higher values of oxygen uptake and heart rate (Mclean et al., 2010). Unfortunately, this setting does not reflect triathlon competition pace, nor the individual characteristics of our PTS4 para triathlete who has right lower leg amputation and could not compensate change of arm SR by significant higher contribution of leg kicking. These findings suggest that SR modulation may serve as a key aspect for coaches to manipulate during training depending on context and race demands. A higher total energy expenditure and greater energy cost could reflect inefficiencies in stroke mechanics (as exhibited by higher jerk cost), which may lead to greater fatigue and suboptimal performance, particularly in the case of longer-distance events (Bouvet et al., 2023; 2025). In our study, the para triathlete was able to functionally decrease his SR, as requested to optimise arm glide when swimming with the current. Especially, he exhibited the highest S and SI, and the lowest IdC, jerk cost and total energy expenditure for a SR_{s-6} confirming that his preferred SR of 44 $cycle.min^{-1}$ is functional. However, as modulation of his preferred SR led to an increase of the total energy expenditure and a decrease of the smoothness and efficiency of the stroke mechanics, individualized training of SR adaptability appeared crucial to expect transfer into competitive performance.

Conclusion

In conclusion, it is important to detect the preferred SR for a given race pace, then to assess the adaptability of SR (i.e. ability to increase and decrease the preferred SR) and arm coordination without dramatic increase of total energy expenditure, without stroke mechanics smoothness and efficiency degradation or decrease in S. These findings advise to train various SR conditions around the preferred SR to functionally adapt arm coordination pattern (notably by varying catch and glide phase duration) to favour potential transfer of behaviour when confronted to the current in ecological context of competition.

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Key points

- In the 10 x 25 m test, the para triathlete displayed high and constant SI at low paces suggesting that he could effectively adapt his SR and his arm coordination pattern to swim with the current.
- At high paces, he started losing effectiveness of SR beyond his preferred SR of 44 cycle.min^{-1}.
- In the 6 x 50 m test modulated in SR, high SR conditions were difficult to achieve and were associated to higher total energy expenditure and higher jerk cost than lower SR conditions.
- Training various SR conditions around the preferred SR allow to functionally adapt arm coordination pattern to favour potential transfer when confronted to the current in ecological context of competition.

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