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Swim specialty affects energy cost and motor organization

L. Seifert¹, J. Komar¹, P. M. Leprêtre², F. Lemaitre¹, F. Chavallard¹, M. Alberty³,
N. Houel⁴, C. Hausswirth⁵, D. Chollet⁶, P. Hellard⁴

¹ Faculty of Sport Sciences, University of Rouen, Cetaps Upres EA3832, Mont Saint Aignan, France

² Faculté des Sciences du Sport, Université de Picardie Jules Verne, Laboratoire de Recherche Adaptations Physiologiques à l'Exercice et Réadaptation à l'Effort, EA3300, Amiens, France

³ Laboratory of Human Movement Studies, Faculty of Sport Sciences, University of Lille, France

⁴ Fédération Française de Natation, Département d'Etudes et Recherches, Paris, France

⁵ INSEP, Biomechanics and Physiology, Paris, France

⁶ Université de Rouen, CETAPS Laboratory EA3832, Mont Saint Aignan, France

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Abstract

The purpose of this study was to analyse the effect of swimmer specialty on energy cost and motor organization. The stroking parameters (velocity, stroke rate, stroke length, stroke index) and the index of coordination (IdC) of 6 elite sprinters were compared with those of 6 elite long-distance swimmers during an incremental swimming exercise test (6×300 m separated by 30 s of passive recovery) that progressively increased the energy cost. Energy cost (C), with its aerobic (*Caero*) and anaerobic (*Canaero*) components, was determined by measuring oxygen uptake (VO₂) and blood lactate ([La]). Motor organization was assessed by analysis of video recordings from aerial and underwater side-view cameras. The results showed that throughout the test, both groups increased C, *Canaero*, stroke rate and IdC and decreased *Caero* and stroke length (all P<0.05). On the mean of the 300-m sets, sprinters had higher values for C (14.8 vs. 12.9 J•kg⁻¹•m⁻¹), *Canaero* (33.8 vs. 23.4%), [La] (5.9 vs. 3.1 mmol•L⁻¹), stroke length (2.31 vs. 2.28 m) and IdC (-11.2 vs. -21.7%) and lower values for *Caero* (66.2 vs. 79.6%), VO₂ net (2 825 vs. 2 903 mL•min⁻¹), stroke rate (0.55 vs. 0.62 Hz) and stroke index (2.96 vs. 3.19 m•s⁻¹) than long-distance swimmers (all P<0.05). For the same relative intensity, sprinters accumulated more lactate and swam more slowly than long-distance swimmers; they showed greater change in their arm coordination but their swimming economy was lower.

Key words: coordination - motor control - biomechanics - swimming - energy cost - specialty

Introduction

The energy cost of human locomotion differs greatly between land and water. Since the density of water is about 800 times that of air, aquatic locomotion requires much greater energy expenditure to overcome active drag. Di Prampero [13] compared several forms of locomotion at speeds corresponding to the world record for aerobic events of comparable duration and showed that the energy cost was highest in swimming (20 J•kg⁻¹•m⁻¹ for 1 500-m free style at 1.67 m•s⁻¹), being respectively 4.7 and 8.7 times greater than for running 5 km and cycling 10 km. As the density of water is greater than air, the mechanical efficiency (η_M), which is the conversion of energy expenditure (\dot{v}) (input) to mechanical work (W_{tot}) (output) (Equation 1), is low in swimming (8-12%) [4][39][42][44]:

$$\eta_M = W_{tot} / \dot{E} \quad (1)$$

The mechanical work (W_{tot}) is partitioned into the work done to overcome external forces (the external work, W_{ext}) and the work done to accelerate and decelerate the limbs with respect to the center of mass (the internal work, W_{int}) [44]. The external work is related to the kinetic energy of the water and, because water does not allow for a solid push-off, W_{ext} is composed of the work needed to overcome drag (W_d)

that contributes to propulsion and the work wasted in the water (W_k). The relationship between W_d and W_k is defined as the Froude efficiency (η_F) (Equation 2) [44]:

$$\eta_F = W_d / (W_d + W_k) \quad (2)$$

Finally, the propelling efficiency (η_P) is [39][44]:

$$\eta_P = W_d / W_{tot} \quad (3)$$

Thus, the combination of Equations 1 and 3 (in Equation 4) highlights the importance of propelling efficiency and the work used to overcome drag forces as factors determining energy expenditure and the energy cost in swimming:

$$\dot{E} = W_d / (\eta_P \cdot \eta_M) \quad (4)$$

Toussaint et al. [39] showed that η_P varies between 46% and 77% for top-level swimmers. Moreover, Toussaint [38] observed lower η_P for triathletes (44%) than for competitive swimmers (61%). Cappaert et al. [7] reported differences in η_P for sprint (48%), middle-distance (56%) and long-distance swimmers (62%), whereas η_M did not change within groups, being close to 4-5%.

Therefore, the swimmer specialty (sprint vs. long-distance) and the type of training, both of which are related to different organismic characteristics (muscular, anthropometric, metabolic and cardiorespiratory) [3][6][11][12], may influence propelling efficiency in a task-dependent manner [7][38][41]. Sprinters, for example, are characterized by greater maximal strength and higher glycolysis and ATP-PCr enzymatic activity than long-distance swimmers [12][24]. Costill et al. [11] showed that the contribution of muscular strength to 25-m and 400-m swimming performance dropped to 86% and 58%, respectively, suggesting that strength capacity contributes more to sprint performance. In fact, for middle- and long-distance events, the swimming speed at the lactate threshold and VO_2 max were the most important factors for high-level performances [11][12]. Thus, according to Equation 4, the results of Cappaert et al. [7] suggested that the higher \dot{v} of the sprinters may have been due to their higher W_d and lower η_P .

However, the forward body displacement and thus the energy cost during aquatic locomotion are not only related to the Froude and propelling efficiencies, but also depend on the timing between the actions responsible for the external work, namely inter-limb coordination. Chollet et al. [10] assessed inter-arm coordination in front crawl, using an index of coordination (IdC) which quantified the time gap between 2 propulsive phases. These authors emphasized that another way to achieve efficient motor organization is to maintain a high average swimming speed by minimizing the time gap between 2 propulsive phases [10]. Propulsive discontinuities are among the factors (such as fluctuation of force impulse, active drag, etc.) that cause large intra-cyclic speed variations [29][34], thereby increasing the energy cost [5]. Hence, the opposition mode of inter-arm coordination, meaning the absence of a lag time between arm propulsions (i. e., perfect propulsive continuity), seems the most economic [8]. From this perspective, catch-up coordination could appear less economic as a lag time occurs between the propulsions of the left and right arms [10] and could lead to intra-cyclic speed variations. In fact, there is not an “ideal” coordination mode because coordination depends on the relations between interacting constraints (task, environment and organismic [33][36]). For example, at high speed (above 1.8 m•s⁻¹), where environmental constraints are elevated due to high active drag, superposition coordination mode (i. e., partial overlap of the 2 arm propulsions) appears to be the only effective and economic choice [33]. Organismic characteristics also influence arm coordination, as demonstrated for gender [30] and physical impairments and disabilities [28][34]. Several comparative studies have shown that only elite sprint swimmers reach high swimming speeds and switch to the superposition coordination mode [18][33], whereas less skilled swimmers [33] and triathletes [18] remain in catch-up mode. For the latter, this result could be explained by the high proportion of training in aerobic endurance [18] where speed is less than 1.8 m•s⁻¹. One case study highlighted that IdC increased when swim speed and energy cost increased [23]. Thus, when speed and energy cost increase, it is expected that swimmers will adapt their inter-arm coordination to follow the imposed pacing and to keep their propulsion as economic as possible. Given that sprint swimmers usually swim at speeds requiring greater anaerobic energy expenditure than long-distance swimmers [6], the aim of this study was to analyse the effect of swimmer specialty on energy cost and motor organization (arm coordination and stroking parameters).

Material and Methods

Participants

12 elite male front crawl swimmers voluntarily participated in this study in 2007 and composed 2 groups: 6 specialists in long distance (from 5 to 25 km) and 6 specialists in sprint (50 m and 100 m). The long-distance swimmer characteristics were: 20.7 ± 5.7 years, 176 ± 5 cm, 67.3 ± 8.7 kg. This group included 4 swimmers on the national junior team, 2 international finalists in the World Cup, and a European champion of the 10-km. The times in the 400-m and 1 500-m events for this group were 243.70 ± 4.63 s and 954.64 ± 15.03 s, respectively. The sprinter characteristics were: 22.2 ± 4.4 years, 183 ± 7 cm, 73.3 ± 9.5 kg. The times in the 50-m and 100-m events for this group were 22.97 ± 0.59 s and 51.86 ± 1.68 s, respectively. The protocol was approved by the University ethics committee and explained to the swimmers, who then gave their written consent to participate. This study was conducted in accordance with recognized ethical standards and the national/international laws reported by Harriss and Atkinson [17].

Swim trials

In a 50-m open pool (26°C), the swimmers performed an incremental test. The test consisted of 6 consecutive 300-m trials separated by 30-s resting intervals. The starts were performed from the wall of the pool and, because they were breathing through a snorkel, the swimmers were asked to do hand turns rather than flip turns. Individual personal-best 400-m freestyle performances recorded within the month preceding the testing period were used to determine the paces of the incremental sets. The pace of the first 300 m was 30 s slower than the time required to swim 300 m at the adjusted 400-m race pace. This time was then reduced by 5 s for each consecutive 300 m until the final 300 m. Swimmers were verbally encouraged to reach their maximal speed during the final 300 m. Thus, each set of 300 m represented the same relative intensity for both sprint and long-distance swimmers. During a pilot study, the amount of time lost because of snorkel use (0.58 s per 50 m) was determined for each swimmer by comparing 2 conditions, with and without the snorkel, during a 50-m trial at maximal speed. The time lost from executing hand turns instead of conventional flip turns (1.18 s per turn) was determined for each swimmer by comparing 2 conditions, flip turn without snorkel and hand turn with snorkel, at maximal speed. They were thus taken into consideration to adjust the speed of the sets. Swimming speed was monitored with an Aquapacer 'Solo' (Challenge and Response, Inverurie, UK). Markers were positioned every 2.5 m along the edge of the pool, and an operator then walked along the deck with a stick immersed in the water to indicate the prescribed swim speed to the swimmer. As done in previous studies, the operator used the auditory signal of the Aquapacer in correspondence with the visual markers on the deck to match his walking pace [2]. The swimmers were asked to maintain speed by keeping their heads at the level of the immersed stick of the operator with a range <1 m.

Video recording and stroking parameters

Aerial and underwater (0.5 m) side-view cameras (Panasonic NV-GS17, 50 Hz) were superposed and fixed on the right side of the pool. These cameras video-taped 2 strokes taken in the central part of the pool. A video timer was included in the underwater view; this view was then synchronized and genlocked to the aerial view with Adobe Premiere©. A calibration frame of 5 m in the horizontal axis and 2 m in the vertical axis was positioned on the floor of the pool, orthogonally to the external side-view camera, for measuring time over a 5-m distance to obtain the swim speed (v , in $\text{m}\cdot\text{s}^{-1}$). When the front of the swimmer's head reached the edge of the frame and left the second edge of the frame, time was recorded. The arm stroke rate (SR, in Hz) was calculated from hand entry at the first stroke to hand entry at the second stroke. The stroke length (SL, in $\text{m}\cdot\text{stroke}^{-1}$) was calculated from the average speed (v) and the arm stroke rate (SR):

$$SL = v \cdot SR \quad (5)$$

According to Costill et al. [11], the stroke index (SI, in $\text{m}^2\cdot\text{s}^{-1}$) is an indicator of swim efficiency and relates to the product of swimming speed (v) and stroke length (SL):

$$SI = v \cdot SL \quad (6)$$

Arm coordination

Arm movement was broken down into 4 phases (entry, pull, push and recovery) [10]. The absolute duration of each phase was measured with a precision of 0.02 s from the 2 synchronized side-views, and then the relative duration of each phase was expressed as a percentage of complete stroke duration. The duration of the propulsive phase is the sum of the pull and push phases, and the duration of the non-propulsive phase is the sum of the entry and recovery phases. Arm coordination was quantified using the index of coordination (IdC) [10]. When a lag time occurred between the propulsive phases of the 2 arms, the stroke coordination was called 'catch-up' ($\text{IdC} < 0\%$). When the propulsive phase of one arm started when that of the other arm ended, the coordination was called 'opposition' ($\text{IdC} = 0\%$). When the propulsive phases of the 2 arms

overlapped, the coordination was called 'superposition' ($IdC > 0\%$). The IdC was calculated for 2 strokes per 50 m taken in the 10-m central part, then averaged for the 3 laps of 50 m composing the last 150 m, to correspond to the analysis of the oxygen uptake. The IdC was expressed as a percentage of complete arm stroke duration.

Energy cost

During exercise, minute ventilation ($\dot{V} \dot{V} E$), oxygen uptake ($\dot{V} O_2$) and carbon dioxide production ($\dot{V} CO_2$) were recorded breath-by-breath by the K4b2 telemetric gas exchange system (Cosmed, Roma, Italy) [16][27], which was calibrated according to the manufacturer's instructions before each test. Ectopic artefacts were manually eliminated and data were then averaged every 5 s. A capillary blood sample was obtained from the finger no more than 30 s after the end of the first 5 sets and 3 min after the last set and analysed for blood lactate concentration (Lactate Pro LT, Arkay Inc., Kyoto, Japan) [25]. The samples were also taken at rest and at the end of each 300 m during the all-out exercise. The energy cost per unit distance (C , $mLO_2 \cdot kg^{-1} \cdot m^{-1}$) was defined as:

$$C = E' / v \quad (7)$$

where E' is the total metabolic energy expenditure (aerobic and anaerobic pathways) expressed in $mLO_2 \cdot min^{-1} \cdot kg^{-1}$ and v , in $m \cdot min^{-1}$, is the swimming speed [13][15] at sub-maximal and maximal intensities. The aerobic component of swimming energy cost ($Caero$) was equal to the ratio between VO_{2net} (i. e., the difference between the VO_2 measured during the last minute of each swimming stage and its value at rest) and the swimming speed [13][15]. $Caero$ was calculated from the steady state of $\dot{V} O_2$ [13][15], which corresponded to the last 150 m composing the 300 m. The net energy cost of anaerobic glycolysis ($Canaero$) was estimated from blood lactate. Blood lactate measures (mmol) were converted to oxygen equivalent values as $3 mLO_2 \cdot kg^{-1}$ of bodyweight per mmol of blood lactate [14]. Thus, C calculated as the addition of $Caero$ and $Canaero$ represented the energy expended to cover one unit of distance while swimming at a given speed and with a given stroke (anaerobic alactic energy sources seem to be neglected, or are assumed to be reduced, when evaluating \dot{V} for 200-m or longer events [26]). Finally, C is given in $J \cdot Kg^{-1} \cdot m^{-1}$, assuming that 1 mLO_2 consumed by the human body yields 20.9 J (which is true for a respiratory ratio of 0.96) [6][13].

Statistical analysis

All values are given as mean \pm SD. A normal distribution (Ryan Joiner test) and the homogeneity of variance (Bartlett test) and authorized parametric statistics (Minitab 15.1.0.0, Minitab Inc., 2006) were verified. 3-way ANOVA (set \times group \times subject) analysed the effects of the incremental tests on the physiological and stroking parameters and IdC comparing the 2 groups (fixed factor: set and group; random factor: subject; $n=6$ sets \times 2 groups \times 6 subjects=72). The Pearson correlation test and linear regression then studied the relationships between energy cost (C , $Caero$, $Canaero$) and the IdC for each subject. Last, the values of the slope (modelling the linear regression) of the sprinters' group were compared with those of the long-distance swimmers' group with the Kruskal-Wallis test. For all tests, the level of significance was fixed at $P < 0.05$.

Results

Swim set effect

From the first to the last 300 m, all subjects increased speed ($F_{5,52}=33.2$, $P < 0.001$) by increasing the stroke rate ($F_{5,52} = 46.7$, $P < 0.001$) and decreasing the stroke length ($F_{5,52} = 15.9$, $P < 0.001$) ([Fig. 1]). For both groups ([Table 1]), a significant increase in energy cost (C) was observed ($F_{5,52} = 55.1$, $P < 0.001$) and $Caero$ decreased whereas $Canaero$ increased ($F_{5,52} = 9.5$, $P < 0.001$); however, the aerobic pathway remained the main contributor to C ($> 60\%$). The increase in C was related to a significant increase in VO_{2net} ($F_{5,52} = 21.6$, $P < 0.001$) and blood lactate concentration ($F_{5,52} = 47.6$, $P < 0.001$). The IdC increased for both groups ($F_{5,52} = 10.3$, $P < 0.001$) over the 6 sets of 300 m, but it remained negative, meaning that the arm coordination was in catch-up mode ([Fig. 2]).

Group effect

On the mean of the 6 sets of 300 m, the long-distance swimmers showed a higher mean speed (1.39 ± 0.10 vs. 1.27 ± 0.09 $m \cdot s^{-1}$; $F_{1,52} = 62.4$, $P < 0.001$), stroke rate (0.62 ± 0.07 vs. 0.55 ± 0.04 Hz; $F_{1,52} = 10.5$, $P = 0.02$) and stroke index (3.19 ± 0.38 vs. 2.96 ± 0.32 $m^2 \cdot s^{-1}$; $F_{1,52} = 43.7$, $P < 0.001$) and a lower stroke

length (2.28 ± 0.21 vs. 2.31 ± 0.15 m \cdot stroke $^{-1}$; $F_{1,52}=8.3$, $P=0.006$) and IdC (-21.7 ± 2.3 vs. $-11.2 \pm 3.6\%$; $F_{1,52}=561.8$, $P<0.001$) than the sprint swimmers ([Fig. 1]). On the mean of the 6 sets, the long-distance swimmers expended lower C ($F_{1,52}=13.9$, $P<0.001$), lower Canaero ($F_{1,52}=15.3$, $P<0.001$) and higher Caero ($F_{1,52}=15.3$, $P<0.001$) than the sprint swimmers ([Table 1]). The long-distance swimmers also had lower blood lactate concentration (3.1 ± 2.7 vs. 5.9 ± 2.2 mmol \cdot L $^{-1}$) ($F_{1,52}=10.4$, $P=0.02$) and greater VO₂ net ($2\,903 \pm 641$ vs. $2\,825 \pm 691$ mL \cdot min $^{-1}$) ($F_{1,52}=6.2$, $P=0.048$) than the sprinters on the mean of the 6 sets.

The Pearson test of correlation showed positive relationships between IdC and C for the sprint (individual correlation coefficients ranged from $0.86 < r < 0.98$, all $P<0.05$, $n=6$) and long-distance swimmers (individual correlation coefficients ranged from $0.81 < r < 0.92$, all $P<0.05$, $n=6$). [Fig. 2] indicates the linear regression between IdC and C for the sprint (individual regression coefficients ranged from $0.75 < R^2 < 0.96$, all $P<0.05$, $n=6$) and long-distance swimmers (individual regression coefficients ranged from $0.66 < R^2 < 0.85$, all $P<0.05$, $n=6$), and [Fig. 3] indicates the linear regression between IdC and Caero, and between IdC and Canaero, for the sprint (individual regression coefficients ranged from $0.67 < R^2 < 0.96$, all $P<0.05$, $n=6$) and long-distance swimmers (individual regression coefficients ranged from $0.66 < R^2 < 0.92$, all $P<0.05$, $n=6$). The Kruskal-Wallis test showed a significantly higher slope for the sprint swimmers in comparison with the long-distance swimmers, concerning the linear regression between IdC and C, between IdC and Caero, and between IdC and Canaero (all $P<0.05$).

Discussion

The main finding of our study was that the progressive 6 \times 300-m test elicited a predominantly aerobic state that increased energy cost and Canaero, which was more pronounced in the sprinters than in the long-distance swimmers. Sprinters (i) train more using the anaerobic pathway and (ii) are accustomed to a wider range of speeds and are able to reach higher maximal speeds. This aerobic test may have caused earlier muscular fatigue in these swimmers, who had lower performances (swim speed), lower efficiency (stroke index) and greater changes in arm coordination (increase in IdC) throughout the test than the long-distance swimmers.

Energy cost and stroking parameters

Our C values were in accordance with the literature, notably with the results of Zamparo et al. [43], who reported that elite long-distance swimmers had C of 15.4 J \cdot kg $^{-1}$ \cdot m $^{-1}$ for a speed of 1.43 m \cdot s $^{-1}$ assessed during a 2-km trial. For our entire population, stroke rate increased while stroke length decreased when speed and C increased. This finding also agreed with the findings of Zamparo et al. [43], who compared a test of 3 \times 400 m with progressive speed pre- and post-2-km trial (swum at the speed of 10 km). These authors showed that fatigue in elite long-distance swimmers led to an increase in stroke rate and a decrease in stroke length. Barbosa et al. [4] observed similar changes in the stroking parameters with fatigue during a progressive test of 7 \times 200 m. The authors modelled these changes, showing significant quadratic relationships between speed and stroke rate ($R^2=0.82$) and between speed and stroke length ($R^2=0.65$) and linear relationships between energy cost and stroke rate ($R^2=0.20$). Our results also indicated a higher mean C in the sprinters than in the long-distance swimmers, which was in accordance with Chatard et al. [9], who observed a C 15.7-16.5% greater for sprinters. In running, C was also about 10% greater in sprinters than in long-distance runners [19].

Aerobic and anaerobic components of C

According to Capelli et al. [6], the increase in C corresponded to a decrease in Caero and an increase in Canaero (which are expressed in % of C) in both our groups. However, our long-distance swimmers expended greater Caero for a higher swimming speed than the sprint swimmers, meaning that long-distance swimmers might be capable of reaching a higher percentage of maximal speed at the 400-m race pace (i. e., a higher percentage of maximal aerobic speed, taking into account that Lavoie and Montpetit [20] showed that the speed of the 400-m swum at maximal intensity is highly correlated with maximal aerobic speed) with lower blood lactate accumulation. This is in accordance with the results of Shepard et al. [35], who showed higher blood lactate concentration and lower oxygen expenditure for sprinters vs. medium- and long-distance swimmers during maximum exercise. Similarly, Olbrecht et al. [24] demonstrated that for the same blood lactate concentration, shorter exercise times resulted in higher mean anaerobic energy delivery, but that better aerobic endurance also increased the anaerobic contribution. This may explain why in our experiment the long-distance swimmers had lower C and produced lower blood lactate concentration than sprinters: our protocol imposed swim trials in a predominantly aerobic state and long-distance swimmers are used to this physiological task. Conversely, sprinters use the anaerobic energy system more during training and racing, and glycolysis and ATP-PCr enzymatic activity have a lower energy delivery rate than the aerobic energy system [12][20][24]. It could thus be hypothesized that the sprinters became fatigued

more quickly during our aerobic tests and thus had lower swim economy and efficiency. Although they had greater stroke lengths than the long-distance swimmers, these latter had lower energy cost (C, Caero), higher efficiency (stroke index) and higher performance (swim speed). This hypothesis was confirmed by Cappaert et al. [7], who showed that aerobic swims show greater propelling efficiency ($\eta_p=43.5\%$) than anaerobic swims ($\eta_p=33.4\%$). Cappaert et al. [7] also reported higher η_p for long-distance swimmers (62%) than for sprinters (48%).

Arm coordination

The index of coordination (IdC) increased for both groups, suggesting that increases in speed and fatigue led to changes in arm coordination (according to [23]) associated with changes in stroking parameters (as previously shown). However, the IdC of the long-distance swimmers was very negative for all sets of 300 m (mean IdC $< -20\%$), showing greater catch-up coordination mode than in the sprinters ($-15\% < \text{IdC} < -5\%$). Moreover, the slopes of the linear regressions IdC - C, IdC - Caero and IdC - Canaero were significantly steeper for the sprinters ([Fig. 2], [3]), suggesting they changed their arm coordination more than the long-distance swimmers. Thus, a question arose: Why did the long-distance swimmers reach higher speed at each set, displaying greater efficiency (higher stroke index) and economy (lower C) than the sprinters, even though the latter changed their arm coordination and relied less on catch-up mode?

First, as previously suggested, it could be hypothesized that the sprint swimmers modified their arm coordination more than the long-distance swimmers because they were more trained in anaerobic exercise; they thus exhibited earlier muscular fatigue during a progressive swimming test that essentially imposed aerobic swims. Conversely, the long-distance swimmers, who were more trained in aerobic exercise, kept their coordination in great catch-up because they were highly focused on their hydrodynamic position in order to minimize resistive forces and maximize efficiency [21].

Indeed, several studies [1][32] concerning sprint exercise have shown that IdC increases with fatigue and, notably, the relative duration of the propulsive phases (pull and push) increases as the swimmers slow their hand speed [37] and apply lower force and power output [40]. Alberty et al. [1] reported an increase in IdC from -6.5 to -3.3% during a 4×50 m at maximal intensity, while for a 100-m race, Seifert et al. [32] observed that the lowest performers (who seemed the most tired as they took 8.5 s more than the national swimmer group to complete the 100 m) increased IdC from relative opposition (-1.2%) to superposition coordination (2.8%) between the third and last 25-m lap.

These changes in arm coordination may be related to lower average hand speed, as Suito et al. [37] reported a decrease from 2.54 to $2.29 \text{ m}\cdot\text{s}^{-1}$ between the 2 parts of the 100 m. Toussaint et al. [40] showed that as fatigue developed during a maximal-intensity 100 m, speed decreased by 12.4% and power by 23.5%, hand speed dropped from $2.14 \text{ m}\cdot\text{s}^{-1}$ at the first lap to $1.91 \text{ m}\cdot\text{s}^{-1}$ at last lap and propelling efficiency from 81% at the first 3 laps to 76% at the last lap. Changes in stroke organization and notably IdC with fatigue were also observed for aerobic exercise [2][22]. During time limit to exhaustion tests swum at 95%, 100% and 110% of maximal aerobic speed, stroke length decreased while stroke rate increased over the test and arm coordination switched from catch-up mode (IdC $\sim -4\%$) to opposition mode (IdC $\sim -1\%$) [2]. Alberty et al. [2] hypothesized that fatigue development reduced the swimmers' capacity to generate a propulsive impulse per stroke. To compensate, the swimmers accorded greater time to propulsion per distance unit to maintain the overall propulsive impulse [2]. This was accomplished by increasing the IdC, which prompted Alberty et al. [2] to emphasize that these modifications in stroke organization did not guarantee better propulsion. In fact, as observed for sprint exercises, Monteil [22] showed a decrease in hand speed in the insweep phase from $2.5 \text{ m}\cdot\text{s}^{-1}$ to $2 \text{ m}\cdot\text{s}^{-1}$ through an exhausting 400-m test in flume, and a decrease in the resultant force in the insweep and final outswEEP phases. Our hypothesis may be tenable, given these findings about changes in arm coordination and propulsion during fatigue in sprint and aerobic exercise.

Second, it could be hypothesized that the sprint swimmers further modified their arm coordination because they usually focus on propulsion to overcome high active drag during sprint races. In fact, sprinters usually travel through a larger range of speeds in training and are accustomed to reaching higher maximal speeds than long-distance swimmers; thus, their arm coordination may appear more sensitive to environmental constraints (change in speed and high aquatic resistance). For example, Hue et al. [18] showed that triathletes maintained catch-up coordination when speed was increased from the 800-m race pace to the 100-m race pace, possibly because they mostly reach lower speeds, train the aerobic pathway, and have lower propelling efficiency than swimmers. Conversely, swimmers increased their IdC with speed until reaching a relative opposition mode of coordination [18]. Toussaint [38] showed that during several 400-m trials swum at 0.7 - $1.35 \text{ m}\cdot\text{s}^{-1}$, triathletes used a higher proportion of their power output than swimmers to overcome drag for an equal power input, supporting that triathletes have lower propelling efficiency. However, it is important to note that the higher coordination variability observed for sprinters mostly concerned high speeds, as only elite sprinters usually swim $\sim 2 \text{ m}\cdot\text{s}^{-1}$ and have an effective superposition

mode [31][33]. Indeed, Seifert et al. [31][33] observed a switch from catch-up to superposition coordination mode above the critical speed of $1.8 \text{ m}\cdot\text{s}^{-1}$ and/or the critical stroke rate of 0.83 Hz. In our progressive $6\times 300 \text{ m}$, the sprinters reached lower speeds than the long-distance swimmers; moreover, the speed of both groups remained below $1.6 \text{ m}\cdot\text{s}^{-1}$. Therefore, our second hypothesis that the changes in the sprinters' arm coordination could be related to greater motor flexibility remains limited. Indeed, McCabe and Sanders [21], who compared sprinters and long-distance swimmers during sprint (4 repeats of 25 m) and aerobic (400 m) exercise, observed only temporal hand kinematic differences between the 2 groups during the sprint exercise, confirming that mostly high speeds impose great aquatic resistance that could induce changes in stroke organization.

Conclusion

In response to the interaction of environmental and task constraints (respectively, speed increases and instructions to swim 300 m for each set), the entire sample of swimmers increased C, which corresponded to a decrease in Caero and an increase in Canaero. They also modified their stroking parameters by increasing stroke rate and decreasing both stroke length and inter-arm coordination (IdC) toward less of a catch-up mode. The progressive $6\times 300 \text{ m}$ test imposed aerobic sets that led to a greater increase in energy cost and Canaero for the sprinters than for the long-distance swimmers. Because sprinters spend more time training the anaerobic pathway, are accustomed to a greater speed range, and reach higher maximal speeds, this aerobic test caused them earlier muscular fatigue. They thus displayed lower performance (swim speed), lower efficiency (stroke index), higher propulsive continuities (higher IdC) and a greater change in arm coordination (increase in IdC) than the long-distance swimmers over the course of the test. Last, the volume of aerobic or anaerobic training and specialization in long-distance or sprint swimming have a great impact on the relationship of fatigue development and motor organization in swimmers. This suggests that coaches should consider arm coordination, as well as stroking parameters, when a specialization towards sprint or long-distance is chosen.

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Figures and Table

Fig. 1 Change in the stroking parameters along the 6 sets of 300 m for the sprint and long-distance swimmers; v: speed in $\text{m}\cdot\text{s}^{-1}$, SR: stroke rate in Hz, SL: stroke length in $\text{m}\cdot\text{stroke}^{-1}$, SI: stroke index in $\text{m}^2\cdot\text{s}^{-1}$.

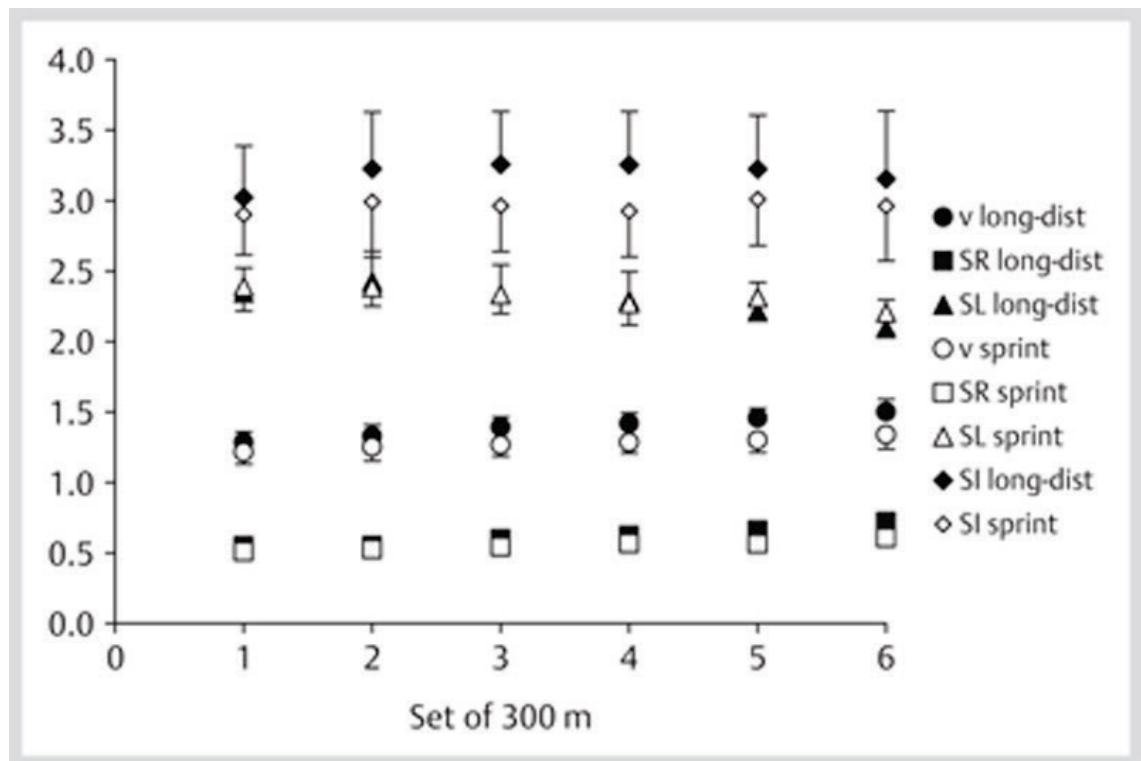


Fig. 2 Linear regression between the index of coordination (IdC) and energy cost (C) for the sprint and long-distance swimmers.

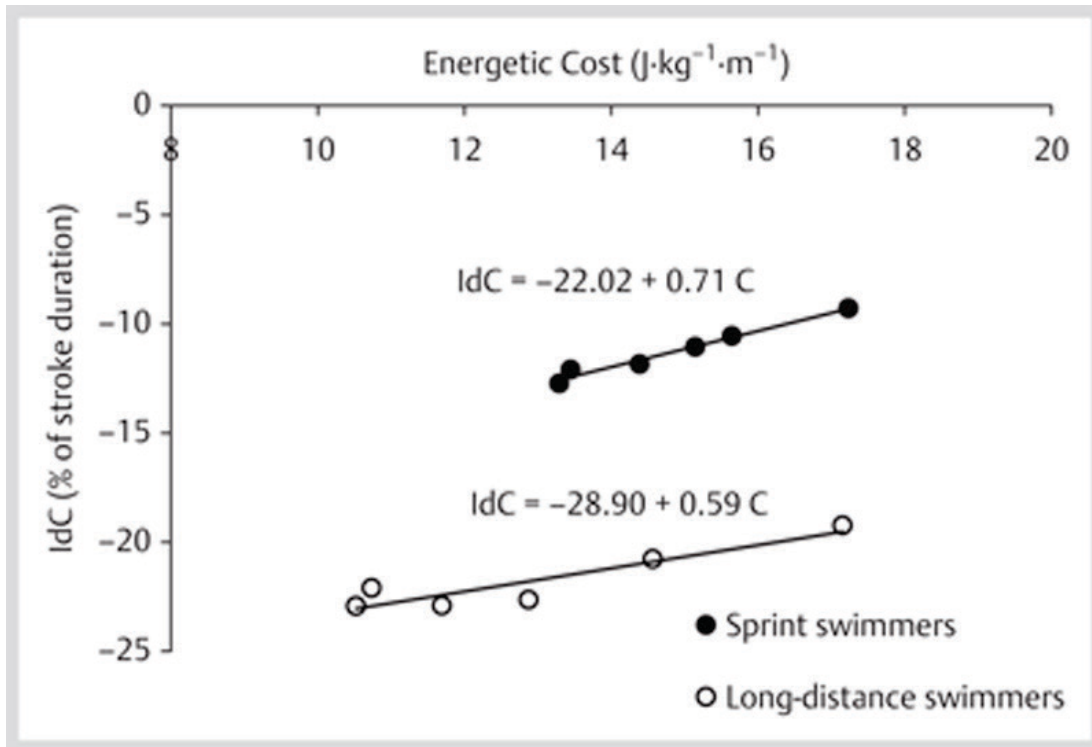


Fig. 3 Linear regression between index of coordination (IdC) and the aerobic component of energetic cost (C_{aero}), and between IdC and the anaerobic component of energetic cost (C_{anaero}) for the sprint and long-distance swimmers.

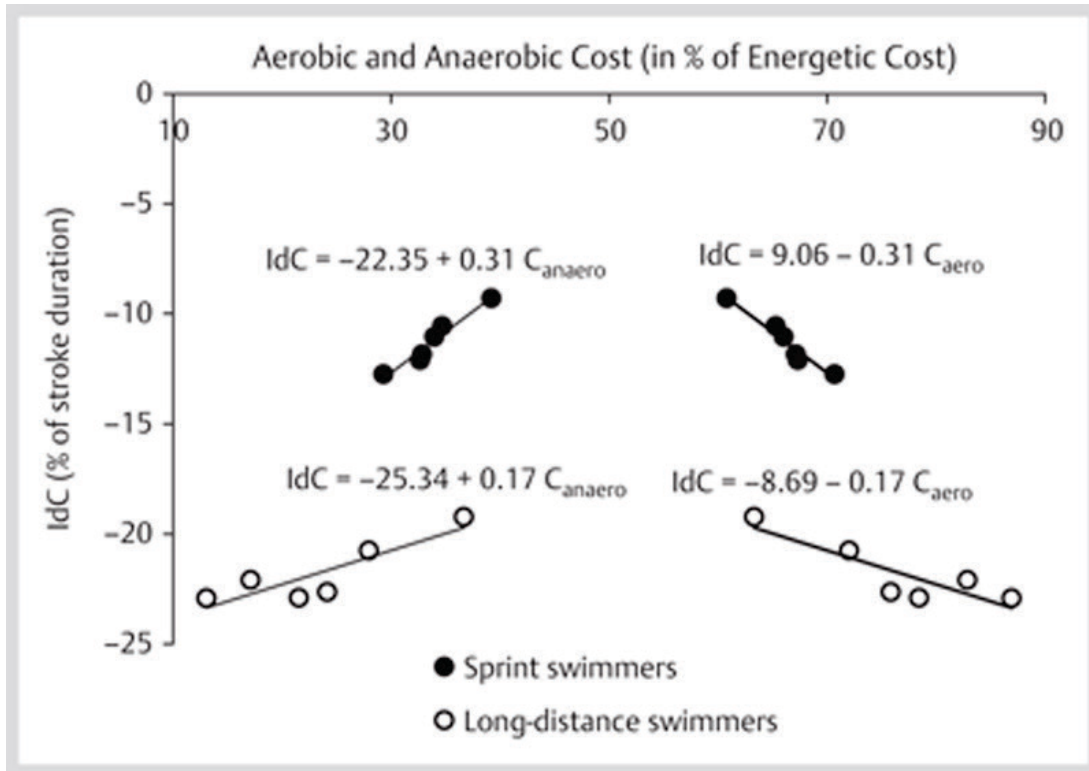


Table 1 Change in the energy cost (C) and its aerobic (C_{aero}) and anaerobic (C_{anaero}) components along the 6 sets of 300 m increased in speed, for the sprint and long-distance swimmers.

Set of 300 m	Long-distance swimmers						Sprint swimmers					
	C ($J \cdot kg^{-1} \cdot m^{-1}$)		C_{aero} (%)		C_{anaero} (%)		C ($J \cdot kg^{-1} \cdot m^{-1}$)		C_{aero} (%)		C_{anaero} (%)	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
1	10.5	2.3	86.9	6.1	13.1	6.1	13.3	2.4	70.7	8.2	29.3	8.2
2	10.7	2.7	82.9	7.5	17.1	7.5	13.4	2.2	67.3	11.0	32.7	11.0
3	11.7	2.7	78.5	6.9	21.6	6.9	14.4	1.9	67.2	9.9	32.9	9.9
4	12.9	2.0	75.9	8.5	24.1	8.5	15.1	1.7	66.0	9.9	34.0	9.9
5	14.6	2.2	72.0	9.0	28.0	9.0	15.6	1.6	65.3	8.6	34.7	8.6
6	17.2	2.4	63.3	8.3	36.7	8.3	17.2	2.1	60.8	7.8	39.2	7.8
mean	12.9	3.3	79.6	10.7	23.4	10.7	14.8	2.3	66.2	9.4	33.8	9.4