Effect of increasing energy cost on arm coordination in elite sprint swimmers

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Article Info
Article history:
Available online xxxx

PsycINFO classification:
2330
3720

Keywords:
Coordination
Biomechanics
Motor control
Energy cost
Swimming efficiency

The purpose of this study was to analyze the changes in stroke parameters, motor organization and swimming efficiency with increasing energy cost in aquatic locomotion. Seven elite sprint swimmers performed a 6 × 300-m incremental swimming test. Stroke parameters (speed, stroke rate and stroke length), motor organization (arm stroke phases and arm coordination index), swimming efficiency (swimming speed squared and hand speed squared) and stroke index were calculated from aerial and underwater side-view cameras. The energy cost of locomotion was assessed by measuring oxygen consumption and blood lactate. Results showed that the increase in energy cost of locomotion was correlated to an increase in the index of coordination and stroke rate, and a decrease in stroke length (p < .05). Furthermore, indicators of swimming efficiency and stroke index did not change significantly with the speed increments (p < .05), indicating that swimmers did not decrease their efficiency despite the increase in energy cost. In parallel, an increase in the index of coordination IdC and stroke rate were observed, along with a decrease in stroke length, stroke index and hand speed squared with each increment, revealing an adaptation to the fatigue within the 300 m.

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1. Introduction

According to Bernstein (1967), motor coordination in complex movement systems is achieved through the management of multiple degrees of freedom. Within this theoretical context, the reduction of the degrees of freedom of a multi-articular system has been characterized as a phenomenon emerging from the interaction of constraints. Newell (1986) argued that the constraints in question should not be viewed as preventing the movement but rather as reductions of the number of possible system configurations. He distinguished three types of constraints – organismic, environmental and task – that should be considered in conjunction when seeking to understand changes in inter-limb coordination. Organismic constraints refer to properties of the organism itself, notably height, weight, and other anthropometric characteristics, and level of expertise or specialty. Environmental constraints are external to the organism and defined prior to the task, such as hydrodynamic resistance in aquatic locomotion (Toussaint & Truijens, 2005). Finally, task constraints pertain to the goal of the activity and specific constraints imposed, like rules, instructions or the use of instruments (Chollet, Chalies, & Chatard, 2000; Seifert, Chollet, & Bardy, 2004; Seifert, Chollet, & Rouard, 2007).

Applied to cyclic human activities, in particular front crawl swimming, such constraints have been studied through their effects on arm coordination and stroke parameters. In this line of research, it has been found that arm coordination is affected by environmental constraints like forward resistance, which is a function of the swimming speed squared. In particular, when swimming speed was increased, the swimmer adapted his arm coordination to overcome the additional demand related to the increase in resistive forces inherent to the density of water. Notably swimmers shifted from a catch-up to a superposition coordination mode in relation to the high active drag that must be overcome to swim fast (Chollet et al., 2000; Seifert, Chollet et al., 2004). Above a critical value of speed (1.8 m s−1) and stroke rate (SR) (0.83 stroke s−1), only the superposition coordination mode occurred (Seifert, Chollet, & Rouard, 2007). Likewise, studies have demonstrated that arm coordination in the front crawl is affected by organismic constraints such as gender (Seifert, Boulesteix, & Chollet, 2004), specialty (Hue, Benavente, & Chollet, 2003), expertise (Seifert, Chollet, & Chatard, 2007), and laterality (Seifert, Boulesteix, Carter, & Chollet, 2005).

In addition, several studies have shown that modification of the energy cost of locomotion (C) is related to changes in motor coordination (Morais et al., 2008; Seifert, Komar et al., 2010). Morais et al. (2008) investigated the effect of a new task and environmental constraint: the effect of an increase in speed during a given distance (i.e., n × 200-m) on arm coordination in front crawl and C. With increasing speed the required propulsion increases. One solution to adapt the propulsion to the requirement of a higher speed is to gradually bring the propulsion impulses of the left and right arm closer to each other, which explains the positive correlation between arm coordination and C that was found in this case study. Notably, the elite female shifted her coordination from catch-up at the energy cost of 7.1 J kg−1 m−1 to a superposition mode at the energy cost of 13.9 J kg−1 m−1. In a similar protocol (n × 300 m), Seifert, Komar et al. (2010) showed that sprinters accumulated more lactate and swam more slowly than long-distance swimmers; they showed greater change in their arm coordination but their C was higher. The significant correlation between arm coordination and C in swimming suggested that the swimmers can adapt their propulsion and their energy expenditure rate (E) by modifying the coupling between the propulsion phases of the arms in order to satisfy the prevailing task and environmental demands. The aim of the present study was to examine the interaction of environmental (i.e., increase in speed) and task (i.e., swimming on a given distance) constraints on motor organization (e.g., arm coordination and stroke parameters) and C in a group of swimmers, as well as the relationship between those changes in motor organization and C and swimming efficiency.

Indeed, since IdC is an index of coordination based on the propulsion duration rather than the propulsive forces, it does not really measure the propulsion. However, a modification of propulsion duration may mean that the swimmer does not produce sufficient supplementary force to satisfy the increased task and environmental demand. To check this hypothesis, it seems interesting to have an estimation of swimming efficiency, as part of the power is dissipated in the water (kinetic energy) to move the limb far from the body, rendering the swimming propulsion less efficient than in walking or running (Pendergast et al., 2003; Toussaint et al., 1988). So, the part of the mechanical external...
power generated by the swimmer that is wasted into the water depends on the quality of the propulsion. The total power of locomotion ($P_{\text{tot}}$) is defined as the sum of the power required to overcome drag ($P_d$), the power wasted in the water ($P_k$) and the internal power ($P_{\text{int}}$) (Pendergast et al., 2003):

$$P_{\text{tot}} = P_d + P_k + P_{\text{int}}$$

(1)

The external mechanical power ($P_{\text{ext}}$) is defined as the sum of $P_d$ and $P_k$ (Pendergast et al., 2003; Toussaint et al., 1988; Toussaint, Janssen, & Kluft, 1991):

$$P_{\text{ext}} = P_d + P_k$$

(2)

The Froude Efficiency ($\eta_F$) corresponds to the efficiency with which this external mechanical power ($P_{\text{ext}}$) produced by the swimmer is transformed into useful propulsion ($P_d$) (Pendergast et al., 2003; Zamparo, Pendergast, Mollendorf, Termin, & Minetti, 2005). A relationship between $C$ and $\eta_F$ was observed in that, for a given speed, the higher the $\eta_F$ the lower the $C$ (Troup, 1999; Zamparo, Pendergast, Termin, & Minetti, 2006). $\eta_F$ is given by the ratio between $P_d$ and $P_{\text{ext}}$:

$$\eta_F = \frac{P_d}{P_{\text{ext}}}$$

(3)

Martin, Yeater, and White (1981) proposed a simple model to assess this efficiency, which was then modified by Zamparo et al. (2005) to:

$$\eta_F = \left( \frac{v}{2\pi \cdot SR \cdot l} \right) \cdot \left( \frac{2}{\pi} \right)$$

(4)

Considering $l$ as the arm length, $\eta_F$ is thus given by the ratio between swimming speed (m s$^{-1}$) and hand speed (u, in m s$^{-1}$) during the underwater part of the stroke cycle (calculated as $2\pi \cdot SR \cdot l$). Moreover, considering that $v^2$ is proportional to the resistive forces and $u^2$ is proportional to the propulsive forces, Toussaint, Carol, Kranenborg, and Truijens (2006) expressed the efficiency of the propulsive actions ($e_{pg}$) not by the ratio $v/u$ but by the ratio $v^2/u^2$:

$$e_{pg} = \frac{v^2}{u^2}$$

(5)

The stroke index (SI, speed × stroke length) also appears to be a relevant swimming efficiency parameter (Costill et al., 1985). Thus, given the relationship between swimming efficiency and $C$ observed by Zamparo et al. (2006), but also in view of the evolution of swimming efficiency, it appears interesting to investigate the changes of motor coordination and $C$ when the constraints increase. The aim of the present study was to assess the effects of the interaction of both the environmental constraint (incremental increases in speed) and task constraint (the maintenance of this speed during the 300-m) on the stroke parameters (stroke rate (SR) and stroke length (SL)), arm coordination (IdC) and swimming efficiency ($v^2/u^2$ and SI) in front crawl. We hypothesized that if the swimmers would respond to the imposed task and environmental constraints, then a significant relationship between $C$ and motor organization would emerge, with the swimmers trying to maintain the level of swimming efficiency throughout the 300-m stretch.

2. Methods

2.1. Participants

Seven French national front crawl swimmers volunteered to participate in the study. Level of expertise was expressed in percentage of the current world record (W.R.) of their best 100-m performance. The mean ± standard deviation (SD) of age, weight, height, arm length, 100-m performance and level of expertise were: 21.6 ± 4.3 yrs, 76.1 ± 11.1 kg, 1.84 ± 0.09 m, 0.63 ± 0.05 m, 53.75 ± 3.10 s, 89.0 ± 4.1 %W.R., respectively. The protocol, after approval by the University ethics committee, was explained to the swimmers, who gave their written participation consent.

2.2. Swimming trials

In a 50-m open pool, the protocol consisted of a progressive step by step incremental test. Swimmers performed six consecutive 300-m swims separated by 30-s resting intervals. As swimmers breathed into a snorkel, in-water starts and open turns were performed. Individual personal best 400-m freestyle performances, recorded within the month preceding the testing period, were used to determine the paces of the incremental stages. During a pilot study, the extra amount of time due to the use of a snorkel was determined for each swimmer for a maximal 50 m, being 0.56 s per 50 m. The extra time due to the carrying of the experimental equipment when executing an open turn instead of the flip turn was 1.17-s per turn. These data were taken into consideration to adjust the speed stages. The pace of the first 300 m was 30 s slower than the time required to swim 300 m at the adjusted 400 m pace. This time was then reduced by 5 s for each consecutive 300 m. Swimmers were encouraged to reach their maximal speed during the final 300 m. Swimming speed was monitored using an Aquapacer ‘Solo’ (Challenge and Response, Inverurie, UK) so that each swimmer could match auditory signals with visual markers positioned every 2.5 m along the edge of the pool.

2.3. Video recording and stroke parameters

Aerial and underwater (0.5-m) side-view cameras (Panasonic NV-GS17, 50 Hz) were fixed on the right side of the pool. The cameras were used to video-tape two strokes in the central part of the pool. A video timer was incrusted in the underwater view, which was afterward synchronized and gen-locked to the aerial view using Adobe Premiere®. A 5 (horizontal) × 2 m (vertical) calibration frame was positioned on the floor of the pool, orthogonal to the external side-view camera that enabled to measure the time over a distance of 5 m to obtain a clean speed (\(v\) in m s\(^{-1}\)). Time was recorded from the instant when the head of the swimmer reached the edge of the frame until it left the second edge of the frame. The SR (in stroke s\(^{-1}\)) was calculated from hand entry at the first stroke to hand entry at the second stroke. The stroke length (SL, in m stroke\(^{-1}\)) was calculated from \(v\) and SR:

\[
SL = v \cdot SR
\] (6)

2.4. Arm coordination

Following Chollet et al. (2000), arm movement was broken down into four phases (entry, pull, push and recovery). The absolute duration of each phase was measured with a precision of 0.02 s from the two 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 IdC (Chollet et al., 2000). When a lag time occurred between the propulsive phases of the two arms, the stroke coordination was called ‘catch-up’ (IdC < 0%). When the propulsive phase of one arm started when the other arm ended its propulsive phase, the coordination was called ‘opposition’ (IdC = 0%). When the propulsive phases of the two arms overlapped, the coordination was called ‘superposition’ (IdC > 0%). The IdC was calculated for two strokes per 50 m taken in the 10-m central part, then averaged for the three 50-m laps composing the last 150 m to correspond to the analysis of the oxygen uptake (VO\(_2\)). The IdC was expressed as a percentage of complete arm stroke duration.

2.5. Energy cost of locomotion

During exercise, minute ventilation (\(V_E\)), VO\(_2\) and carbon dioxide production were recorded breath-by-breath by the K4b\(^2\) telemetric gas exchange system (Cosmed, Roma, Italy) (Duffield, Dawson, Pinnington, & Wong 2004; Rodriguez, Keskinen, Kusch, & Hoffmann, 2008), which was calibrated according to the manufacturer’s instruction before each test. Etopic artefacts were eliminated manually following which data were averaged every 5 s. A capillary blood sample was obtained from the finger no more than 30 s after the end of the first five increments and 3 min after the last
increment and analyzed for blood lactate concentration (lactate Pro LT, Arkay Inc., Kyoto, Japan) (Pyne, Boston, Martin, & Logan 2000). So, the samples were so taken at rest and at the end of each 300 m during the all-out exercise. The C of locomotion (mLO₂ kg⁻¹ m⁻¹) was defined as:

\[
\text{C} = \dot{E} \cdot v^{-1}
\]

where \(\dot{E}\) is the total metabolic energy expenditure (aerobic and anaerobic pathways) expressed in mLO₂ min⁻¹ kg⁻¹ and \(v\), in m min⁻¹, is the swimming speed at sub-maximal and maximal intensities (di Prampero, 1986). The aerobic part of swimming \(C (C_{\text{aero}})\) was equal to the ratio between VO₂ net (i.e., the difference between the VO₂ measured during the last minute of each swimming stage and its value at rest) and the swimming speed (di Prampero, 1986; Fernandes et al., 2006). Anaerobic glycolytic net \(C (C_{\text{anaero}})\) was estimated using blood lactate. Blood lactate measures (mmol) were converted to oxygen equivalent values as 3 mLO₂ kg⁻¹ of bodyweight per mmol of blood lactate (di Prampero & Ferretti, 1999). Thus, \(C\), calculated as the addition of \(C_{\text{aero}}\) and \(C_{\text{anaero}}\), represented the energy expended to cover one unit of distance while swimming at a given speed and with a given stroke. Following Fernandes et al. (2006), anaerobic alactic energy sources were to be neglected, or assumed to be reduced, when evaluating \(\dot{E}\) for 200-m or higher events. Finally, \(C\) is given in J kg⁻¹ m⁻¹ assuming that 1 mLO₂ consumed by the human body yields 20.9 J (di Prampero, 1986).

2.6. Estimation of swimming efficiency

Swimming efficiency was estimated for four participants through two indirect indicators: the efficiency of propulsion generation (\(e_{\text{pg}}\)) (i.e., the \(v^2/u^2\) ratio) and the (SI) (Seifert, Toussaint, Alberty, Schnitzler, & Chollet, 2010). To measure the hip (\(v\)) and wrist (\(u\)) instantaneous speed, three body marks (hip, shoulder, wrist) were digitalized in 2D on video data using Simi Motion software (Simi Reality Motion Systems GmbH, Germany). Video data of the first, third and sixth increments were then analyzed. Swimmers’ \(u\) was calculated by subtracting \(v\) to hand speed observed on video, in order to have the backward hand speed (\(u\)) (i.e., in the swimmers reference and not in the pool reference). Although literature showed the hip as not accurately representing the swimmers center of mass in front crawl (Figueiredo, Vilas Boas, Maia, Goncalves, & Fernandes, 2009; Psycharakis & Sanders, 2009), the strong correlation often observed between hip and center of mass speed fluctuations in the four strokes lead us to use the hip as a practical tool that the coach could use for training and testing protocol (Craig, Termin, & Pendergast, 2006).

According to Costill et al. (1985), the SI (in m² s⁻¹) relates to the product of \(v\) (\(v\) in m s⁻¹) and SL (m stroke⁻¹):

\[
\text{SI} = v \cdot \text{SL}
\]

2.7. Statistical analysis

All values are given as mean ± SD. A normal distribution (Ryan Joiner test) and the homogeneity of variance (Bartlett test) were verified and authorized parametric statistics (Minitab 15.1.0.0, Minitab Inc., 2006). Two-way ANOVA (increment: fixed factor × subject: random factor) were used to analyze the differences between the different increments. Two-way ANOVA (lap: fixed factor × subject: random factor) were used to analyze the differences between the six laps composing a 300 m stretch. Regression tests studied the relationships among the \(C\) and IdC, SR and SL. For all tests, the level of significance was set at \(p < .05\).

3. Results

3.1. Speed increment effect

3.1.1. Arm coordination and stroke parameters

A speed increment effect occurred for SL (\(F(5,30) = 6.68\), SR (\(F(5,30) = 29.33\), IdC (\(F(5,30) = 16.82\)) and \(v\) (\(F(5,30) = 21.84\)).

3.1.2. Energy cost of locomotion

A significant increase of $C$ ($F(5, 30) = 28.96$) occurred from $12.95 \pm 1.83$ J kg$^{-1}$ m$^{-1}$ at increment one to $17.43 \pm 2.07$ J kg$^{-1}$ m$^{-1}$ at the last increment, as well as an increase of VO$_2$ ($F(5, 30) = 17.88$) and of lactate blood concentration ($F(5, 30) = 24.25$). This increase of $C$ related to a significant decrease of aerobic part ($F(5, 30) = 12.20$) coupled with an increase of anaerobic part of $C$ is observed (aerobic part from $67.6 \pm 12.4\%$ at increment one to $58.0 \pm 10.2\%$ at increment six).

3.1.3. Regressions

Individual regression models were calculated between IdC and $C$, SR and $C$, SL and $C$ (Figs. 1 and 2, and Table 1). Regression equations on charts are based on the mean value of individual regressions of six significant subjects for IdC, all subjects for SR, and only 2 significant subjects for SL (Table 1).

Fig. 1. Index of Coordination (IdC) as a function of energy cost ($C$).

Fig. 2. Swimming speed ($v$), stroke rate (SR) and stroke length (SL) as a function of energy cost ($C$).
Table 1
Regression model for the relationship of the index of coordination (IdC), stroke rate (SR) and stroke length (SL) with energy cost (C).

<table>
<thead>
<tr>
<th>Subject</th>
<th>Regression IdC-C</th>
<th>Regression SR-C</th>
<th>Regression SL-C</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Equation</td>
<td>$r^2$</td>
<td>p</td>
</tr>
<tr>
<td>1</td>
<td>$IdC = -25.84 + 1.39 \times C$</td>
<td>85.8</td>
<td>.008</td>
</tr>
<tr>
<td>2</td>
<td>$IdC = -18.61 + 0.48 \times C$</td>
<td>82.7</td>
<td>.012</td>
</tr>
<tr>
<td>3</td>
<td>$IdC = -23.55 + 0.49 \times C$</td>
<td>91.4</td>
<td>.003</td>
</tr>
<tr>
<td>4</td>
<td>$IdC = -18.68 + 0.64 \times C$</td>
<td>95.8</td>
<td>.010</td>
</tr>
<tr>
<td>5</td>
<td>$IdC = -33.78 + 1.22 \times C$</td>
<td>95.5</td>
<td>.001</td>
</tr>
<tr>
<td>6</td>
<td>NS</td>
<td>&gt;.05</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>$IdC = -21.29 + 0.76 \times C$</td>
<td>75.3</td>
<td>.025</td>
</tr>
<tr>
<td>Mean</td>
<td>$IdC = -23.62 + 0.83 \times C$</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Fig. 3. Hand-speed (u), Stroke Index (SI) and $e_{pg}$ (i.e., $v^2/u^2$) for the 6 laps of the 1st, 3rd and 6th increments.

Fig. 4. Stroke rate (SR), stroke length (SL) and IdC for the 6 laps of the 1st, 3rd and 6th increments.
3.1.4. Swimming efficiency parameters

No significant differences occurred between the different increments for the swimming efficiency parameters (mean SI = 2.98 ± 0.31 m²·s⁻¹, mean $v^2/u^2 = 0.33 ± 0.05$).

3.2. Lap effect

A significant increase of SR ($F(5,63) = 3.34$), IdC ($F(5,63) = 4.73$), $v^2/u^2$ ($F(5,63) = 5.60$) and a significant decrease of SI ($F(5,63) = 3.46$), $u$ ($F(5,63) = 2.77$) and SL ($F(5,63) = 3.56$) occurred through the laps for the increments 1, 3 and 6 (Figs. 3 and 4).

4. Discussion

4.1. Increment effect

The first purpose of this study was to examine how arm coordination and stroke parameters are influenced by an increase of $C$. The interaction of both the environmental constraint (increase in speed between increments) and task constraint (the maintenance of this speed during the 300 m) led to an increase in the exercise intensity and fatigue during the test, which can be explained by the augmented drag forces due to the increased $v$ (Barbosa, Fernandes, Keskinen, & Vilas-Boas, 2008) and the effect of the previous exercise increment. Finally, our protocol led to $C$ increase, for which $C$ values are in accordance with those of Zamparo, Capelli, Cautero, and Di Nino (2000) and Fernandes et al. (2006) for speeds between 1.10 m s⁻¹ and 1.50 m s⁻¹.

As expected, a strong relationship between $C$ and motor organization was observed. Notably, the increase of $C$ was significantly correlated to an increase of SR and a decrease of SL. Individual correlation test and linear modeling showed a direct relationship between SR and $C$ for all the swimmers, and an inverse relationship between SL and $C$ only for two swimmers. During a progressive $7 \times 200$-m test, Barbosa et al. (2008) observed similar significant changes in SR ($r^2 = .20$), and non-significant changes in SL ($r^2 = .07$), in accordance with our small number of significant subjects. Moreover, with increasing IdC and $C$, sprinters’ arm coordination tended to change toward an opposition mode (as in Seifert, Komar et al., 2010). Thus, even if the different speed increments did not involve a qualitative shift in coordination mode (i.e., from catch-up to superposition mode), a significant quantitative change in the IdC values occurred in relation with a significant change of the ratio between $C_{anaero}$ and $C_{aero}$. This quantitative change of IdC was gradual and without shift toward the superposition coordination mode because (i) the range of speed between increment 1 and increment 6 was small, and (ii) the speed of the last increment was low (i.e., 1.34 m s⁻¹), whereas the superposition mode appeared as the main coordination mode only over a critical speed of 1.8 m s⁻¹ (Seifert, Chollet, & Rouard, 2007). Individual correlation and linear modeling revealed a strong direct relationship between IdC and $C$ for six subjects (mean $r = .94$). This relationship was also shown by Morais et al. (2008) with a very high correlation value obtained in one female swimmer ($r = .97$). More precisely, both the different values of $r^2$ and different values of the coefficient of $C$ in the regression equations suggest that the swimmers responded differently to the task. Indeed, even if all the swimmers responded adequately to the task, they did not achieve this in the same way, as shown by swimmer 6, who did not significantly adapt his coordination mode but only his SR. Thus, different coping strategies emerged, showing that there is not only the coordination that is the result of interacting constraints. For instance, the swimmers could apply a high impulse per stroke, favoring a high stroke rate or distribute propulsive impulses in time to create the same average propulsive force. In this last case, it means that the same power output was produced using a higher SR and less work per stroke. By assessing the swimming efficiency through the different increments, it was observed that all these motor adaptations allowed the swimmers to maintain their level of efficiency in order to satisfy the task demand. Indeed, in accordance with results of Seifert, Toussaint et al. (2010) obtained during an incremental test, both the $e_{pg}$ and the SI remained stable during the six increments of the test, showing that the swimmers remained efficient despite the increase of $C$. The difference in $e_{pg}$ values (i.e., $v^2/u^2$) observed in the literature could be explained by the lower $u$ found in the present study.
(2.51 ± 0.18 m s\(^{-1}\) vs. 2.98 ± 0.37 m s\(^{-1}\) for Seifert, Toussaint et al. (2010) and 1.91 < \(u\) < 2.14 m s\(^{-1}\) for Toussaint et al. (2006)) because of the different calculation method used (SimiMotion vs. Eq. (4)).

4.2. Lap effect

The protocol used was an incremental intermittent one, which mostly imposed aerobic paces that were not usual for our sprint swimmers (Seifert, Komar et al., 2010). Indeed, the assessment of the \(C\) (using VO\(_2\) and lactate accumulation values) requires increments of a minimum of 2–3 min (di Prampero, 1986; di Prampero, Salvadego, Fusi, & Grassi, 2009) that implies the use of 200-m or 300-m distances even for sprint swimmers. Thus, the previously inter-increment comparison of the mean values of the different increments seems to mask some of the adaptations revealed by the intra-increment study; namely that while remaining speed stable there was an increase in \(\Delta C\) during the increment, accompanied by an increase in SR and a decrease in SL and \(u\). Previous studies have also shown in aerobic exercises that the fatigue induced an increase in SR and \(\Delta C\) and a decrease in SL (Alberty, Sidney, Pelayo, & Toussaint, 2009; Monteil, 1992). Moreover, Monteil (1992) observed, during a 400 m, a decrease in \(u\) especially in the first half part of the cycle, associated with a decrease in hand force propulsion. According to those results, Alberty et al. (2009) attributed the motor adaptations to the decrease in \(u\) induced by a reduction of propulsive forces produced by the swimmers, in consequence to the establishment of fatigue. Even during sprint exercises closer to the usual exercises of sprinters, Toussaint et al. (2006) reported during a 100 m at maximal speed, a decrease of \(u\) from 2.14 to 1.91 m s\(^{-1}\), and a decrease of power output by 23.5%. In that sense, Alberty, Sidney, Huot-Marchand, Hespel, and Pelayo (2005) also showed that with fatigue, in a 4 × 25-m test, sprinters increased \(\Delta C\) and tended to adopt a superposition coordination mode. Thus, the greater relative time spent in propulsion (i.e., due to the increase in \(\Delta C\)) would not indicate better propulsion as shown by the increase in \(\epsilon_{pg}\). This increase of \(\epsilon_{pg}\) could be explained by the decrease of \(u\) combined to the stability of the swimming speed during the step. This increase in hand speed appeared to be due to fatigue more than to an increase in efficiency, as shown by the decrease in SL and SL through the increment. Thus, by inter-lap increasing \(\Delta C\) and SR, the swimmers tried to overcome the decrease of hand speed itself due to the reduction of propulsive force applied, with the expectation that the latter was due to the establishment of fatigue.

5. Conclusion

Throughout the six 300-m increments, swimmers showed adaptations of their stroke parameters by increasing SR and decreasing SL while they increased \(\Delta C\) values and their \(C\). However, the change of arm coordination did not lead to a shift of coordination mode; the catch-up mode was maintained throughout the test. All these inter-increment adaptations were accompanied by stabilization of swimming efficiency parameters in order to satisfy the task demand.

Moreover, the intra-increment analysis revealed a decrease in SL, and an increase in SR and \(\Delta C\), suggesting a fatigue effect. Indeed, swimming efficiency parameters were found to decrease within the increments, which may result from the main aerobic solicitation of the incremental protocol not usual for sprinters. Thus, although the rest between the increments allowed the swimmers to respond to the task demand, our results showed that the increase in fatigue and exercise intensity had a significant impact on the motor organization and efficiency of the sprinters.

References


