Effects of a high-intensity swim test on kinematic parameters in high-level athletes

Yannick A. Aujouannet, Marco Bonifazi, Frédérique Hintzy, Nicolas Vuillerme, and Annie H. Rouard

Abstract: The present study aimed to investigate the effects of a high-intensity swim test among top-level swimmers on (i) the spatial and temporal parameters of both the stroke and the 3-D fingertip pattern and (ii) the mechanical, muscular, and physiological parameters. Ten male international swimmers performed a 4 × 50 m swim at maximal intensity. Isometric arm flexion force with the elbow at 90° (F90°), EMG signals of right musculus biceps brachii and triceps brachii and blood lactate concentrations were recorded before and after the swim test. Kinematic stroke (stroke length, rate, and velocity) and spatiotemporal parameters of the fingertip trajectory were measured by two underwater cameras during the first and last 50 m swims. After the swim test, F90° and mean power frequencies of the EMG decreased significantly when blood lactate concentration increased significantly, attesting the reaching of fatigue. From the first to the last 50 m, stroke rate, stroke velocity, and temporal parameters of the fingertip trajectory exhibited significant increases although stroke length and spatial fingertip trajectory remained unchanged. General and individual adaptations were observed among the top-level swimmers studied. The present findings could be useful for coaches in evaluating fatigue effects on the technical parameters of swimming.

Key words: sport, fatigue, biomechanic, lactate, force.

Résumé : Les objectifs de cette étude étaient d’étudier les effets d’un test intensif de nage sur (i) les paramètres spatiaux du cycle et de la trajectoire en 3-D du majeur et (ii) les paramètres mécaniques, musculaire et physiologique. Dix nageurs internationaux ont effectué un 4 × 50 m à vitesse maximale. La force de flexion isométrique maximale avec le coude à 90° (F90°), le signal EMG du biceps et du triceps brachii et la concentration sanguine de lactate ont été enregistrés avant et après le test de nage. Les paramètres cinématiques du cycle (amplitude, fréquence, vitesse) et les paramètres spatio-temporels de la trajectoire du majeur ont été mesurés à l’aide de deux caméras sous marine durant le premier et le dernier 50 m. Après le test de nage, F90° et les paramètres fréquentiels de l’EMG diminuent significativement alors que la concentration sanguine de lactate augmente, attestant la présence de la fatigue. Du premier au dernier 50 m, la fréquence de cycle, la vitesse de nage et les paramètres temporels de la trajectoire du majeur présentent une augmentation significative alors que l’amplitude de cycle et la trajectoire spatiale du majeur restent inchangées. Des adaptations générales et individuelles sont observées entre les nageurs de haut niveau étudiés. Ces résultats peuvent être utiles pour les entraîneurs désirant évaluer les effets de la fatigue sur les paramètres techniques de la nage.

Mots clés : sport, fatigue, biomécanique, lactate, force.

Introduction

Front crawl swimming consists of right and left arm strokes and a varying number of kicks per arm cycle (e.g., Maglischo 1993). A number of studies in swimming have analysed the relationships between swimming velocity (SV), stroke length (SL), and stroke rate (SR) (e.g., Craig and Pendergast 1979; Craig et al. 1985; East 1970; Keskinen and Komia 1988a, 1993; Wilke 1992). Specific studies concerned the evolution of these parameters during maximal exercises even in competition or under test conditions. Craig et al. (1985) and Wilke (1992) showed a decrease in SV during the latter stages of competitive events. These authors indicated that the impairment of performance for faster swimmers corresponded to a decrease in SR with a constant SL, whereas slower swimmers experienced a decrease in both SR and SL. The decrease in SR could be due to either a decrease in force production (e.g., Toussaint and Beek 1992) or to a failure of neural activation (e.g., Keskinen and Komia 1993); the decrease in SL could be linked to blood lactate accumulation (e.g., Keskinen and Komia 1993; Weiss et al. 1988).

SV resulted from the propulsive and resistive forces. The propulsive forces in front crawl are mainly generated by the arm movements (e.g., Hollander et al. 1987), particularly by the forearms and hands (e.g., Berger et al. 1995). Miyashita (1975) highlighted the strong relationship between isometric
arm pull force and swimming velocity. Propulsive forces were strongly linked to kinematic hand parameters as observed in the different models of hand force calculations (e.g., Schleihauf 1979; Berger et al. 1995). Maglischo et al. (1986) have also shown the importance of the 3-D hand pattern in 50 and 100 m freestyle performance. Other authors have suggested that SV could partly be explained by horizontal or vertical hand displacements during the arm stroke (e.g., Deschodt et al. 1996; Deschodt 1999). However, studies on the evolution of hand patterns in high intensity swim exercises are limited. Deschodt (1999) reported a significant decrease in the displacement of the wrist in the sagittal plane following a 6 × 50 m freestyle swim at maximal velocity. During maximal swim trials, a decrease in hand velocity was observed during the insweep phase in 400 m freestyle (e.g., Monteil et al. 1994) and during the upsweep phase in a 200 m butterfly (e.g., Martins-Silva et al. 1997). Monteil et al. (1994) concluded that the decrease in hand velocity was due to the inability to maintain high force intensity throughout the test. The present study therefore aimed to investigate the effects of a high-intensity swim test among top-level swimmers on (i) the mechanical, muscular, and physiological parameters and (ii) the spatial and temporal parameters of both the stroke and the 3-D fingertip pattern. A principal component analysis (PCA) allowed the determination of general and individual adaptations to high-intensity swim exercises among top-level swimmers.

Materials and methods

Subjects

Ten male international-calibre swimmers volunteered to participate in this study. Five were medallists and the others were finalists at the European Championship (Berlin, Germany, 2002). Their mean physical characteristics were as follows: age, 22.5 ± 2.3 y; height, 1.87 ± 0.07 m; mass, 79.00 ± 6.53 kg.

Testing procedures

The test took place in a 25 m swimming pool. After a standardized warm up consisting of a 1200 m swim, subjects performed an isometric maximal voluntary contraction (MVC) of the biceps brachii (Bi) and triceps brachii (Tri) muscles, which they sustained for 5 s. After the MVC tests, subjects were asked to perform a maximal right shoulder flexion test at an arm–trunk angle of 90° with the elbow joint fully extended (F90°PRE). The arm–trunk angle was chosen to reproduce the middle phase of the stroke (e.g., Fomitchenko 1999; Strasse et al. 1999). The subject was lying prone on a swim bench and a hand paddle attached to a strain gauge allowed the subject to generate force with the hand in prone position (Fig. 1). This system was developed and validated by the Istituto di Scienza dello Sport (CONI, Roma, Italy, 2002). Swimmers were familiarized with the apparatus in their daily training. The lower and upper bodies were straight and the subjects’ faces were positioned facing the bench. The swimmer was fixed to the bench to avoid forward displacement during the pull. They were instructed to increase force gradually up to maximum and to maintain this level for 3 s before relaxing. The contralateral arm rested free along the body. During this test, strong encouragements were provided to the subjects.

After this initial isometric test, each subject performed four 50 m repetitions (4 × 50 m) in freestyle at maximal effort separated by 10 s rest periods. This exercise corresponded to a broken 200 m and was designed to reproduce as closely as possible the effort of a 200 m freestyle competition (e.g., Pelayo et al. 1996) without the psychological constraints of the race (e.g., Alberty et al. 2003). Immediately after the completion of the 4 × 50 m, the F90° test was reproduced (F90°POST).

Data collection

Blood lactate concentration ([BLa]) was obtained from capillary blood samples (5 µL) in the ear lobe at the end of the warm up ([BLa basal]) and at the end of the 4 × 50 m freestyle swim ([BLa max]). This parameter was chosen as a physiological indicator of the contribution of anaerobic glycolysis during exercise (e.g., Di Prampero et al. 1978).

The time was measured for each of the four sprints to quantify the variation of performance related to exercise. A strain gauge force transducer (Haarbye, Copenhagen, Denmark) was used to measure the force exerted by the subjects during the F90° test in pre and post conditions (Fig. 1).

The electrical activity of the right Bi and Tri was measured by an EMG device (ME 3000 P8, Mega Electronics Ltd., Kuopio, Finland) fixed to the lower part of the swimmer’s back. These muscles were chosen according to their main function in the central part of the underwater stroke (e.g., Clarys 1983). The skin was shaved and rubbed with an alcohol solution and two silver – silver chloride surface electrodes with preamplifiers (Medicotest blue sensor type M-00-S, 27 mm diameter) were placed in a bipolar configuration (2 cm interelectrode distance) in line with each muscle’s fibre orientation. Electrodes were placed in the midpoint of the contracted muscle belly, as suggested by Clarys and Cabri (1993). An adhesive film (Tegaderm, 3M, St. Paul, Minn.) avoided contact with water (e.g., Rouard and Clarys 1995). A third reference electrode was attached to the body in an area not in proximity to the studied muscles. The EMG signal was stored on-line with a sampling frequency of 1000 Hz using a data acquisition card (flash memory 32 MB) processed through a computer with high- and low-pass filters of 8 and 500 Hz, respectively. The gain was set at 1000 with a common mode rejection ratio of 92 dB.

Two digital video cameras (Panasonic WV-CP454E) were used to record frontal and sagittal views of the underwater arm stroke during the 1st and 4th sprints. The sagittal camera filmed the right side of the swimmer. Each camera was enclosed in a waterproof box fixed at a depth of 0.60 m. The
Fig. 2. The reference $O_{xyz}$ with the origin $O$ at the right fingertip entry. The right fingertip and right hip digitized points were represented.

Data treatment

Blood lactate concentration was analyzed with a Lactate Pro-analyzer (Akray KDK, Kyoto, Japan) according to the enzymatic method.

The EMG data obtained during the $F90^\circ$PRE and $F90^\circ$POST tests were processed with MegaWin software (Mega Electronics). EMG signals were treated over a 3 s stabilized portion of the maximal force production. The mean power frequency under pre (MPF$_{PRE}$) and post (MPF$_{POST}$) conditions was calculated for both muscles (Bi-MPF$_{PRE}$, Bi-MPF$_{POST}$, Tri-MPF$_{PRE}$, and Tri-MPF$_{POST}$). The EMG signals recorded were full-wave rectified and integrated. The integrated EMG (iEMG) under pre (iEMG$_{PRE}$) and post (iEMG$_{POST}$) conditions was calculated for the Bi (Bi-iEMG$_{PRE}$, Bi-iEMG$_{POST}$) and Tri (Tri-iEMG$_{PRE}$, Tri-iEMG$_{POST}$) muscles. To normalize the signals, all of the iEMG data were reported to the iEMG value of the MVC, expressed as a percentage of the MVC.

According to the Kinematic Analysis software validated by Monteil et al. (1996), the right hip joint and the right fingertip were semi-manually digitized frame-by-frame between two successive right-hand entries. The 3-D hip and hand trajectories were smoothed with a polynomial function (3rd degree). For this testing condition, the reliability of the software was tested and an average error of 3.07% ± 0.6% was observed on the 3 axes. For a transportable acquisition system, this result was acceptable in regard to the range values of the studied parameters.

A right-handed Cartesian base reference frame $O_{xyz}$ was established with the origin $O$ fixed at the fingertip entry, as illustrated in Fig. 2. The horizontal $x$ axis was noted as positive in the forward direction. The transverse $y$ axis was directed perpendicular to the right side of the pool and the $z$ axis was vertically upward. The right fingertip entry was taken as the temporal and spatial reference (0, 0, 0, 0) to determine different points of the 3 dimensions of the underwater fingertip trajectory.

Five spatiotemporal stroke parameters, ($i$) stroke length (SL; measured in m), ($ii$) stroke rate (SR; strokes·min$^{-1}$), ($iii$) stroke velocity (SV; m·s$^{-1}$), ($iv$) underwater stroke duration (UD; s), and ($v$) recovery duration (RD; s), were calculated as follows:

$$[1] \quad SL = X_t - X_0$$

where $X_0$ is the $x$ coordinate at the first right-hand entry and $X_t$ is the $x$ coordinate of the hip at the subsequent right-hand entry.

$$[2] \quad SR = \frac{1}{(n_i - 1) \times \frac{1}{25}} \times 60$$

where $n_i$ is the number of images between the two successive right-hand entries at a 25 Hz sampling rate of video acquisition.

$$[3] \quad SV = SL \times \frac{SR}{60}$$

$$[4] \quad UD = t_{EXIT} - t_{ENTRY}$$

where $t_{EXIT}$ is the temporal coordinate of the fingertip exit and $t_{ENTRY}$ is the temporal coordinate of the right fingertip entry.

$$[5] \quad RD = t_{EXIT} - t_{ENTRY+1}$$

where $t_{ENTRY+1}$ is the temporal coordinate of the next right fingertip entry.

The right fingertip trajectory relative to the reference frame $O_{xyz}$ in the frontal and sagittal planes was described by 8 characteristic points, as previously seen in other studies (e.g., Schleihau 1974; Deschodt et al. 1999; Maglischo 2003) (Fig. 3):

- In the anteroposterior $x$ axis, the coordinate of fingertip entry (En) and exit (Ex), the maximal coordinates in the forward (F) and backward direction (B), and the catch point (C). C was determined when the arm and hand were facing back and corresponded to the beginning of the propulsive phase (e.g., Maglischo 2003).
- In the transverse $y$ axis, the maximal coordinates in the outward direction (O) and inward direction (I).
- In the vertical $z$ axis, the maximal depth (D) of the fingertip.

All of these points (En, C, F, O, D, I, B, and Ex) were characterized by both temporal and spatial coordinates. To study the influence of high-intensity exercise, we calculated...
Fig. 3. Typical example of characteristic points of the fingertip trajectory. On the anteroposterior x axis: En, entry into water; C, catch point; F, maximal forward coordinate; B, maximal backward coordinate; and Ex, exit from the water. On the transverse y axis: O, outward; and I, inward. On the vertical z axis: D, maximal depth.

the differences for the spatial and temporal parameters of trajectories between the 1st and 4th sprints.

Statistical analysis
Mean and standard deviations were calculated for each parameter. A coefficient of variation (CV = standard deviation/mean) was determined to evaluate the homogeneity of the population. The effects of a high-intensity swim test were evaluated by comparison of pre and post values for blood lactate concentration, $F90^\circ$, MPF, and iEMG. For kinematic parameters, the comparison was realised between data obtained during the first and last sprints. All comparisons were realised using a non-parametric test (Wilcoxon test with $p < 0.05$).

For the significantly different kinematic parameters, the variations between the 1st and 4th sprints were computed into a principal component analysis (PCA), which was used in a descriptive way. The results were represented by two graphics: a correlation diagram and an individual representation. The correlation diagram best represented the relationships between the studied parameters. Each axis of the diagram was defined by a combination of the different parameters, especially by those projected nearest the periphery of the diagram. The correlation diagram enabled the location of the coordinates for each subject. This method allowed us to identify the individual responses with respect to parameters defining each axis of the correlation diagram. To evaluate the influence of $[BLa_{\text{max}}]$ on kinematic changes, the subjects were classified in descending order of $[BLa_{\text{max}}]$; subject 1 had the highest and subject 10 had the lowest.

Results
The results suggest significant effects of high-intensity swim exercise on time performance during a 50 m freestyle, $[BLa]$, $F90^\circ$, EMG, and kinematic parameters of stroke and fingertip trajectory. Each of these parameters is presented in Table 1.

Summary of results

High-intensity swim test on whole-stroke and underwater trajectory parameters
The whole-stroke parameters (SL, SR, SV, UD, and RD) for the first and last 50 m sprints are presented in Table 2.

SR and SV decreased significantly between the first and last sprints ($p < 0.05$) and between $F90^\circ$, MPF, and iEMG. The spatial and temporal parameters of fingertip trajectory, indicating great heterogeneity within the population for these parameters. Overall, these results indicated that the high-intensity swim test had effects on temporal parameters for both whole-stroke and underwater trajectory, whereas no significant difference was observed for spatial whole-stroke or trajectory parameters. These findings indicated general adaptations for the whole group without any information on individual adaptations.

The relationships between the parameters significantly modified by the high-intensity test and the individual adaptations were examined by PCA. The five parameters of the PCA corresponded to the differences between the 1st and 4th sprints for parameters significantly different between the two conditions ($\Delta O$, $\Delta I$, $\Delta C$, $\Delta SR$, $\Delta SV$). The variance was principally explained by two factors (87.9%). On the correlation diagram (Fig. 5), axis 1 was mainly defined by the variation of temporal parameters of the underwater trajectory ($\Delta I$, $\Delta O$, $\Delta C$), which were close to the periphery of the diagram. Axis 2 was principally defined by the stroke parameters, $\Delta SR$ and $\Delta SV$, respectively.

The correlation diagram showed that variations among temporal parameters ($\Delta O$, $\Delta I$, $\Delta C$) were highly correlated ($0.921$, $p < 0.001$) between $\Delta O$ and $\Delta I$, ($0.853$, $p < 0.01$) between $\Delta C$ and $\Delta O$, and between $\Delta C$ and $\Delta I$ ($0.755$, $p < 0.01$). In other words, swimmers who presented the higher temporal increase for C on the anteroposterior x axis also presented the higher temporal increase for O and I on the transverse y axis. It was also evident that variations of stroke parameters ($\Delta SV$, $\Delta SR$) were strongly correlated (0.762, $p < 0.01$). The decrease in SV observed during the 4th sprint resulted from the decline of SR. Variations of stroke parameters ($\Delta SR$, $\Delta SV$) were not correlated to those of temporal parameters ($\Delta O$, $\Delta I$, $\Delta C$) ($p > 0.05$), i.e., the decrease in SV and SR could not
Table 1. Mean, standard deviation (SD), and coefficient of variation (CV) of the whole-stroke parameters during the 1st and 4th 50 m tests.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Mean (s)</th>
<th>SD (s)</th>
<th>CV (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>50 m time (s)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1st</td>
<td>2.26</td>
<td>0.29</td>
<td>12.83</td>
</tr>
<tr>
<td>4th</td>
<td>2.18</td>
<td>0.22</td>
<td>10.10</td>
</tr>
<tr>
<td>Mean</td>
<td>2.26</td>
<td>0.29</td>
<td>12.83</td>
</tr>
<tr>
<td>50 m time (s) - change</td>
<td>0.08</td>
<td>0.07</td>
<td>5.29</td>
</tr>
<tr>
<td>1st - 4th</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Stroke length (m)</td>
<td>2.15</td>
<td>0.18</td>
<td>12.17</td>
</tr>
<tr>
<td>Stroke rate (strokes min⁻¹)</td>
<td>34.50</td>
<td>4.17</td>
<td>12.02</td>
</tr>
<tr>
<td>Swimming velocity (m s⁻¹)</td>
<td>1.29</td>
<td>0.19</td>
<td>14.73</td>
</tr>
<tr>
<td>1st - 4th</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SR</td>
<td>3.26</td>
<td>0.22</td>
<td>6.81</td>
</tr>
<tr>
<td>4th</td>
<td>3.45</td>
<td>0.23</td>
<td>6.67</td>
</tr>
<tr>
<td>Mean</td>
<td>3.36</td>
<td>0.22</td>
<td>6.67</td>
</tr>
<tr>
<td>SW, swimming velocity</td>
<td>3.26</td>
<td>0.22</td>
<td>6.81</td>
</tr>
<tr>
<td>UD, underwater stroke duration</td>
<td>16.25</td>
<td>1.55</td>
<td>9.51</td>
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<tr>
<td>RD, recovery duration</td>
<td>17.92</td>
<td>1.81</td>
<td>10.17</td>
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<tr>
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<td>17.92</td>
<td>1.81</td>
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<tr>
<td>RD</td>
<td>17.92</td>
<td>1.81</td>
<td>10.17</td>
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</tbody>
</table>

Table 2. Mean, standard deviation (SD), and coefficient of variation (CV) of the coefficient of variation (CV) of the stroke and the 3-D fingertip pattern.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Mean (mmol L⁻¹)</th>
<th>SD (mmol L⁻¹)</th>
<th>CV (%)</th>
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<tbody>
<tr>
<td>50 m time (s)</td>
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<tr>
<td>1st</td>
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<tr>
<td>4th</td>
<td>1.00</td>
<td>0.10</td>
<td>10.00</td>
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<tr>
<td>Mean</td>
<td>1.00</td>
<td>0.10</td>
<td>10.00</td>
</tr>
<tr>
<td>50 m time (s) - change</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>1st - 4th</td>
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<td></td>
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Discussion

The aim of this study was to investigate the effects of a high-intensity swim test on both (i) mechanical, muscular, and physiological parameters and (ii) spatial and temporal parameters of both the stroke and the 3-D fingertip pattern. Finally, a PCA was computed to further investigate the individual adaptations and the relationships between the parameters modified by the high-intensity test.

After the high-intensity swim test, several indicators suggested the reaching of fatigue by all of the swimmers. First, the decrease in maximal isometric force could be interpreted as a manifestation of fatigue as referenced by many authors (e.g., Grassino et al. 1979; Komi and Tesch 1978; Mannion and Dolan 1996; Merletti et al. 1992) or dynamic contractions (e.g., Bigland-Ritchie et al. 1981, 1983; Hagberg 1981; Mannion and Dolan 1996; Merletti et al. 1992) or dynamic contractions (e.g., Grassino et al. 1979; Komi and Tesch 1978). The [BLamax] values at the end of the set of 4 x 50 m sprints were similar to those recorded after an elite 200 m freestyle race (e.g., Bonifazi et al. 1993), indicating the high intensity of this exercise. These results confirmed that this protocol closely reproduced the effort of a 200 m freestyle competitive event, as previously suggested by Pelayo et al. (1996) and Alberty et al. (2003). Thus, the reduction in muscle pH after the last 50 m (as suggested by the [BLa] measures) could be one factor responsible for impaired muscle function resulting in fatigue (Tesch et al. 1978).

Finally, the significant decrease in 50 m time performance might indicate the reaching of fatigue according to Enoka and Stuart (1992), who noted an acute impairment of performance with fatigue. Overall, the significant changes be explained by the temporal increase of fingertip trajectory parameters.
in mechanical, electromyographic, physiological, and performance indicators between pre and post conditions strongly suggested the presence of fatigue at the end of the high-intensity swim test used in this study.

During the 1st 50 m, the SL results were comparable to those of previous studies involving 200 m freestyle during official competitions with lower SR and SV values (e.g., Craig et al. 1985; Pai et al. 1984). The lower values found here could be explained by the recording EMG system, which increased body drag and limited the performance of the subjects. In addition, the experimentation took place during a high-volume endurance training cycle, which was characterized by lower stroke rates and velocities in accordance with Maglischo (2003). The spatial and temporal parameters of the hand trajectory during the 1st 50 m agreed with previous studies (e.g., Maglischo et al. 1986; Deschodt et al. 1996; Deschodt 1999; Maglischo 2003).

Under fatigue, spatial stroke (SL) and trajectory parameters (F, B, Ex, D, O, I) were not significantly different. These results differed from previous studies, which found a decrease in SL with fatigue in well-trained swimmers (e.g., Deschodt 1999; Keskinen and Komi 1988b, 1993; Weiss et al. 1988). For the spatial parameter of fingertip trajectory, Deschodt (1999) observed a decrease in F (maximal forward coordinate) and D (maximal depth) of the hand during a 6 × 50 m swimming set at maximal velocity and performed by well-trained swimmers. In regard to earlier studies with lower-skilled swimmers (e.g., Deschodt 1999; Keskinen and Komi 1988b; Weiss et al. 1988), the maintenance of the spatial parameters observed in the present study could be due to the very high performance level of our subjects (5 of them were international medallists). The maintenance of the hand trajectory suggested a robust spatial pattern in these elite swimmers that is not easily changed even by the impairments imposed by fatigue (e.g., Rodacki et al. 2001).

In contrast to the spatial parameters, the temporal parameters were significantly altered by fatigue with significant decrease in SR and increase of I, O, and C. A reduction of SR has been reported by Craig et al. (1985) during a 200 m freestyle competition. As suggested by Toussaint and Beek (1992), the decrease in SR could result from decrease in force production or by a failure in neural activation as suggested by Keskinen and Komi (1993). The 2 hypotheses

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**Fig. 4.** (A) Spatial parameters of the underwater fingertip trajectory (expressed in cm) for the 1st (white bar) and 4th (grey bar) 50 m sprints. F, maximal forward coordinate; B, maximal backward coordinate; Ex, exit from the water; D, maximal depth; O, outward; and I, inward. (B) Temporal parameters of F, B, Ex, D, O, I, and C (catch point), expressed in s. Asterisk indicates significant difference between the 1st and 4th sprints at \( p < 0.05 \).

**Fig. 5.** Correlation diagram of the PCA for the variations of the temporal parameters (\( \Delta O \), maximal outward coordinate; \( \Delta I \), maximal inward coordinate; and \( \Delta C \), catch point) and stroke parameters (\( \Delta SR \), stroke rate; and \( \Delta SV \), stroke velocity).

**Fig. 6.** Representation of subjects of the PCA. Axis 1 represents the subjects grouped on the basis of variation of temporal parameters (\( \Delta I \), \( \Delta O \), and \( \Delta C \)) (dashed line). Axis 2 represents the subjects grouped on the basis of variation of stroke parameters (\( \Delta SV \) and \( \Delta SR \)) (solid line).
were supported by the shift of the MPF to low frequencies and the decrease in force production during the isometric test in post conditions.

The PCA results indicated that the decrease in SV was strongly correlated to the decrease in SR, confirming previously reported data (e.g., Cappaert et al. 1995; Keskinen and Komi 1988a, 1988b, 1993). This underlined the fact that SR is the most determinant factor of SV in high-level swimmers under fatigue (e.g., Deschodt 1999). The significant decrease in SR was not related to temporal changes of a particular phase of the stroke (such as increased time of UD, RD or I, O, and C), but rather to the overall temporal pattern.

The temporal variations of the fingertip trajectory (I, O, C) were observed during the first half of the stroke. The high correlation between these parameters confirmed the strong relationships between the 3-D components of the hand movement as observed by previous studies (e.g., Counsilman 1969; Brown and Counsilman 1971). This present result highlights that the longer the time the swimmer placed his hand in a propulsive position, the longer the time the subject took to complete the insweep phase. The increased time for C (catch point) indicates that fatigued swimmers spent more time placing the hand in a propulsive way. This confirmed Goldfuss and Nelson’s (1971) finding, who studied tethered swimming to the point of exhaustion and who observed a consistent increase of time during the entry phase (i.e., the subject took a rest with the upper arm extended before beginning the pull). The time increases for O and I indicated a longer duration of the insweep phase for a similar spatial pattern. As a result, the hand velocity decreased during this phase. This result was in line with Monteil et al. (1994), who found a decrease in hand velocity during the insweep phase in the latter stages of a 400 m freestyle. Cappaert et al. (1995) showed that this phase was the most propulsive part of the stroke and Rouard et al. (1997) observed the greatest muscle recruitment during it. Decreased hand velocity with fatigue could be due to the inability to maintain mechanical and muscular constraints, as suggested by Monteil et al. (1994). Our findings in a maximal shoulder flexion test in post conditions (decrease in $F_{90^\circ \text{POST}}$ and Bi- and Tri-MPF$^{\text{POST}}$ values) could confirm this hypothesis.

In regard to these general adaptations to fatigue, the PCA results could point to some individual adaptations, particularly in reference to the influence of blood lactate concentration on stroke and fingertip trajectory parameters. From axis 1, the PCA result demonstrated that swimmers with the highest [BLamax] values (subjects 1, 2, and 3) presented the greatest temporal variations for I, O, and C; other subjects (4, 5, 6, 7, 8, 9, and 10) were not characterized by such important variations. Furthermore, this result suggested that subjects with highest [BLamax] values (subjects 1, 2, and 3) experienced the greatest decrease in hand velocity under fatigue, particularly during the insweep phase. From axis 2, no relationship was observed between two different indicators of fatigue, ASV and [BLamax]. Indeed, swimmers with the highest [BLamax] did not present the strongest decrease in SV. This result can be illustrated by subjects 1, 2, and 3, who had fairly similar [BLamax] values (16.8, 16.1, and 15.9 mmol·L$^{-1}$, respectively). Although subject 1 presented a strong decrease in SV (from 1.60 to 1.07 m·s$^{-1}$), subjects 2 and 3 were characterized by a slight decrease in SV (from 1.17 to 1.12 m·s$^{-1}$ and from 1.27 to 1.22 m·s$^{-1}$, respectively). Another example of individual adaptation concerned subjects 3 and 4,1 who presented similar [BLamax] values (15.9 and 15.1 mmol·L$^{-1}$, respectively) with different variations of stroke and temporal parameters. Subject 3 presented high variations of temporal parameters and low variations of stroke parameters, whereas subject 4 exhibited the opposite adaptations. For Keskinen and Komi (1988a), large individual variations in [BLamax] and SV parameters reflected great variability in both swimming efficiency and stroke parameters. These results underline that fatigue in swimming leads to individual adaptations for stroke and trajectory parameters among top-level swimmers.

**Conclusion**

This study aimed to investigate the effects of a high-intensity swim test on isometric force production and associated muscular recruitments and on spatiotemporal parameters of the stroke and 3-D fingertip pattern. At the end of the final 50 m sprint, several indicators ($F_{90^\circ}$, MPF, [BLa], 50 m time performance) revealed that our subjects reached fatigue. For 10 top-level swimmers, fatigue was characterized by spatial stability and temporal increase for both stroke and parameters of fingertip trajectory. The maintenance of the spatial stroke and trajectory parameters could be due to the very high performance level of our subjects and suggested a robust spatial fingertip pattern that is not easily changed even by the impairments imposed by fatigue. The increase of temporal parameters under fatigue was specially marked by an important increase of time for the beginning of the cycle.

Under fatigue, general adaptations suggested that SR becomes the most determinant factor of SV for top-level swimmers. Individual adaptations showed that [BLamax] appeared to influence the variations of temporal trajectory parameters, but did not appear to decrease SV. These results suggested that the usual monitoring of fatigue in swimming, based upon blood lactate concentration and SL, is questionable. The present study could be useful for coaches to evaluate the general and individual effects of fatigue on technical parameters of freestyle stroke.

**References**


