Changes in Physiological and Stroke Parameters During a Maximal 400-m Free Swimming Test in Elite Swimmers

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Abstract/Résumé

The aim of this study was to analyse the variations of the metabolic and technical parameters during a maximal 400-m freestyle event. Seven trained male swimmers swam a maximal 400-m freestyle as if in competition (255.8 ± 6.9 s). Intermediate time and stroke rate (SR) were recorded at each length (25 m). To estimate the changes in metabolic parameters during the 400-m event, they swam a 300-, 200-, and 100-m test set from each length of the 400-m event results, resting 90 min between each test. The exact speed at each length was given with a visual light pacer. Oxygen uptake ($\dot{V}O_2$) and blood lactate concentration ([Lac]) were measured before and immediately after each test. $\dot{V}O_2$ and [Lac] were stable during the 100-, 200-, and 300-m test but significantly higher ($p < 0.05$) during 400-m test. The estimated contribution of anaerobic metabolism (EsC_{ANA}) during the first 100-m and the 400-m represented 45% and 20% of total energy output, respectively. Speed decreased significantly ($p < 0.05$) after the first 100-m and remained stable until the end. SR decreased significantly after the first 100-m, then increased until the end, while stroke length

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(SL) decreased linearly throughout the 400-m. During the first or the last 100-m, EsC_{ANA} was not correlated with the changes in V, SR, or SL between the second and the first 100-m, and between the fourth and the third 100-m, respectively. To conclude, this study showed that the swimmers were not able to maintain stable SL during the 400-m event. Thus, to sustain stable velocity and to compensate for the decrease in SL, swimmers increased SR throughout the last 300-m.

Le but de cette étude fut d'analyser les variations des paramètres métaboliques et techniques lors d'une épreuve maximale de 400m nage libre (NL). Sept nageurs entraînés ont nagé un 400m NL comme en compétition (255.8 ± 6.9 s). Le temps intermédiaire et la fréquence de bras (SR) ont été enregistrés à chaque longueur (25m). Pour estimer les changements des paramètres métaboliques lors du 400m, les sujets ont réalisé un test de 300, 200, et 100m programmés à partir des résultats de chaque longueur de l'épreuve de 400m, se reposant 90 min entre chaque test. La vitesse exacte de chaque longueur était donnée par une rampe lumineuse. Les nageurs récupéraient 90 min entre chaque épreuve. La consommation d'oxygène ($\dot{V}O_2$) et la lactatémie ([Lac]) ont été mesurées avant et juste à la fin de chaque épreuve. $\dot{V}O_2$ et [Lac] ont été stables lors des tests de 100, 200, et 300m et significativement plus élevés (p < 0.05) lors du test de 400m. La contribution estimée du métabolisme anaérobie (EsC_{ANA}) lors du premier 100m et lors du 400m représentait 45% et 20% de l'énergie totale dépensée, respectivement. La vitesse a diminué significativement (p < 0.05) après le premier 100m et est restée stable jusqu'à la fin. SR a diminué significativement après le premier 100m puis a augmenté jusqu'à la fin pendant que la distance par cycle (SL) a diminué linéairement tout au long du 400m. Lors du premier et dernier 100m, EsC_{ANA} n'a ni été corrélé aux changements de V, SR, ou SL entre le second et premier 100m, ni aux changements entre le quatrième et troisième 100m, respectivement. En conclusion, cette étude montre que les nageur n'ont pas été capables de maintenir SL pendant l'épreuve de 400m. Ainsi, pour maintenir stable la vitesse et compenser la diminution linéaire de SL, les nageurs ont augmenté SR tout au long du dernier 300m.

Introduction

In swimming, velocity is defined as the product of the stroke rate (SR) and distance traveled at each cycle, i.e., the stroke length (SL). Various factors have been observed to influence this relationship. Researchers have shown that training (Craig and Pendergast, 1979; Craig et al., 1985), intensity (Chollet et al., 1997; Craig et al., 1985; Wakayoshi et al., 1995), swimming distance (Craig et al., 1985), gender (Craig et al., 1985), and style of swimming (Craig et al., 1985; Desy et al., 1995) all influence the SR-SL relationship. The main factor of performance between SR or SL (Craig et al., 1985; Keskinen and Komi, 1993; Toussaint and Beek, 1992) is still contentious. Nevertheless, there is consensus that performances in the future will be carried out with an increase of SL and a decrease of SR (Craig et al., 1985; Toussaint and Beek, 1992). Furthermore, during incremental exercises with stages of short duration (<30 s) and total recovery between each one, the decrease of SL is the result of an increase in SR, but it seems that during competition races it is the reverse.

In the first case, the cause for a decrease in SL can be mainly due to the swimmers' technical capabilities, while in competition races it can be hypothesized

that the cause of the decrease in SL is mainly due to their physiological capabilities. However, to our knowledge there have been no physiological results in swimming that explain the decrease of SL. Currently only fatigue is deemed responsible for this phenomenon (Craig et al., 1985; Toussaint and Beek, 1992).

Some studies have shown a correlation between physiological indices and SR and SL (Costill et al., 1985; Wakayoshi et al., 1995). It was shown that maximal oxygen uptake ($\dot{V}O_2$max) and SL were correlated with performance (Costill et al., 1985). Also, it was shown that SR and $\dot{V}O_2$ were correlated during an incremental exercise (Wakayoshi et al., 1995). It has been reported that in 200-m races and longer, SL decreased throughout the race (Craig et al., 1985; Toussaint and Beek, 1992). Furthermore, the fastest swimmers maintained their speed by maintaining or increasing SR more than their competitors (Craig et al., 1985). However, that study was conducted during competition. Consequently, only SR and SL were measured and no physiological data were available.

Therefore we hypothesized that the swimmer was not able to maintain SL throughtout a 400-m freestyle and that his ability to increase SR to maintain velocity is related to an increase of energy output, i.e., anaerobic and aerobic energy output. To our knowledge, only fatigue was identified as the main factor responsible for the decrease in SL. In order to study whether the decrease in SL was correlated with an increase in $\dot{V}O_2$ or in blood lactate concentration during a maximal 400-m freestyle event, we divided this event into four tests of 100-m. This segmentation method was first proposed in **1991 by Vilas-Boas and Duarte**. Additionally, **Laffite and Demarle (1999) used a portable breath-by-breath gas analyser** (Cosmed K4b^2, Rome, Italy) to measure $\dot{V}O_2$ peak during swimming immediately following the event.

Therefore the aim of this study was (a) to analyse the changes in stroke technique and physiological parameters of elite swimmers during a 400-m freestyle event during consistent conditions of competition, and (b) to study the potential relationships between changes in these parameters.

Methods

SUBJECTS AND TESTING

The subjects who volunteered for this study were 7 trained elite male swimmers on the Portuguese swim team (19.1 ± 1.8 yrs; 72.4 ± 4.7 kg; 178.9 ± 5.6 cm; Mean ± *SE*). All subjects competed at the national level and trained at least 16 hours per week. Only 3 of them were crawl specialists.

All swimming tests were conducted in a 25-m swimming pool during the swimming training and competitive season 10 weeks before the national championship. First, each swimmer performed a maximal 400-m freestyle during which the time and SR were recorded at each length. Swimmers were instructed to perform this event as if in competition. The next three tests were based on the results of the initial 400-m. Subjects swam a 300-m, a 200-m, and a 100-m freestyle test at the same swimming velocity (V) as the previous 400-m within 1 hour and 30 minutes, i.e., 90 min of rest between each test. For motivational reasons, the test order was not random; after the 400-m test, the swimmers began with the longest and hardest test and ended with the shortest and easiest one.

A visual light pacer (TAR 1.1, GBK-Electronics, **which city?**\\ Portugal) with a flash every 5 meters was programmed with the swim split results of the initial 400-m to give the swimmer the exact velocity of each length. During the 300-, 200-, and 100-m tests, SR was recorded and was later compared with SR of the previous 400-m. To validate the 300-, 200-, and 100-m tests as reliable reproductions of part of the initial 400-m, we ensured that each swimmer had similar $\dot{V}O_2$ and blood lactate concentration rest values prior to each test. Furthermore, SR was controlled at each length (25-m) to be identical to the one measured during the 400-m test.

MEASUREMENTS

Determination of VO₂. Oxygen uptake was measured before and immediately after each test with a breath-by-breath K4b² gas analyser (Cosmed Kb4²). $\dot{V}O_2$ measurements were made in land conditions which were validated for K4b² use (Maiolo et al., 2003; McLaughlin et al., 1999). The swimmer was instructed to take his last breath two strokes before touching the wall of the swimming pool. The operator fixed the mask on the swimmer's face while he leaned on the wall and breathed normally during the first 2 minutes of recovery. The delay between the swimmer's last inspiration and the first gas exchange measure never exceeded 3 seconds.

The $\dot{V}O_2$ reached during exercise was considered as the $\dot{V}O_2$ mean value in 6 seconds after $\dot{V}O_2$ peak detection. We did not consider the first measure of $\dot{V}O_2$ values before the highest $\dot{V}O_2$ measurement, which corresponded to the device adaptation to the sudden change of respiratory cycles and of O_2 uptake. The device adaptation never exceeded 2 seconds.

Blood Lactate Concentration. Blood lactate concentration [Lac] was measured before, immediately following, and 2 minutes after the end of each exercise. Fingertip capillary blood samples were collected into a capillary tube and analysed for lactate concentration using a Doctor Lange analyser (GmbH, Berlin, Germany). This analyser was calibrated before the tests with several solutions of known lactate concentrations. Blood lactate concentration reached during the test was the maximal value between the measurements taken immediately following the exercise and 2 minutes after the end of the exercise. The [Lac] measurement was used to estimate the part of the anaerobic and aerobic metabolisms as described further.

Stroke Length. Stroke length (SL) was measured at each length (25 m) with a video system. Reference marks were placed in the middle of the swimming pool and the profiles of the swimmers were filmed when they passed in front of these reference marks.

Time, Stroke Rate, Stroke Index, and Velocity. The time, SR, and velocity (V) were also measured at each length (25 m). Time and SR were measured directly by two experienced operators using a chronofrequence meter of base 3 (Interval 1000, Nielsen-Kellerman, **which city?**\ USA). The final values of time and SR were the mean value of the measurements of each operator. V was calculated as the ratio between the time and distance, including the dive and the turn.

Contribution of Aerobic and Anaerobic Metabolism. To estimate the proportions of aerobic and anaerobic metabolisms at each 100-m and during the maxi-

mal 400-m test, we hypothesized that the $\dot{V}O_2$ kinetics during this event was fitted according to the following single-exponential equation:

$$\dot{V}O_2\,(t) = \dot{V}O_{2B} + A \times (1 - e^{(-(t-TD/\tau)})) \tag{1}$$

where $\dot{V}O_2(t)$ is oxygen uptake (ml·min^{-1}) at time t, in seconds; $\dot{V}O_{2B}$ (ml·min^{-1}) is oxygen uptake at rest; A (ml·min^{-1}) is the amplitude of the monoexponential, i.e. oxygen uptake above $\dot{V}O_{2B}$; TD (s) is the time delay of the monoexponential; and τ (s) is the time constant of the monoexponential, i.e., the time to reach 63% of the plateau of the monoexponential. We considered that swimmers did not have a different value of time constant than runners for the same relative intensity, i.e., 100% $\dot{V}O_2$max (Billat et al., 2001). The unpublished data of our group confirmed this estimation. Thus the mean value of τ was set to 30 s. Therefore, the volume of O_2 consumed during the first 100-m was estimated from the following equation:

$$VO_2 = [(\dot{V}O_2 - \dot{V}O_{2B}) \times t] - DO_2 \tag{2}$$

where t is the time (min) and DO_2 (mlO$_2$) is the oxygen deficit calculated from Equ. 1 as in the following equation:

$$DO_2 = A \times (\tau/60) \tag{3}$$

with $A = (\dot{V}O_2 - \dot{V}O_{2B})$. Thus, Equ. 2 can be rewritten as follows:

$$VO_2 = [(\dot{V}O_2 - \dot{V}O_{2B}) \times t] - [(\dot{V}O_2 - \dot{V}O_{2B}) \times \tau/60] \tag{4}$$

And Equ. 4 can be simplified as follows:

$$VO_2 = (\dot{V}O_2 - \dot{V}O_{2B}) \times [t - \tau/60]$$

$$\text{or } VO_2 = (\dot{V}O_2 - \dot{V}O_{2B}) \times (t - 0.5), \tag{5}$$

with $\tau = 30$ s, then $\tau/60 = 0.5$ min.

After the duration of the first 100-m, DO_2 was neglected even if the $\dot{V}O_2$ value of the 400-m test was significantly higher than the other tests. Thus, after the duration of the first 100-m, $\dot{V}O_2$ was estimated constant and equal to $[(\dot{V}O_2 - \dot{V}O_{2B}) \times t]$.

The equivalent in mlO$_2$ of anaerobic metabolism was estimated from the blood lactate concentration as the following equation:

$$O_2Eq[Lac] = \Delta[Lac] \times 3.1 \tag{6}$$

where $O_2Eq[Lac]$ (in mlO$_2$) is the equivalent in O_2 of the increase of [Lac]; $\Delta[Lac]$ (mmol·L^{-1}) is the increase in [Lac] between two 100-m (or between rest and the end of the 100-m for the first 100-m); and 3.1 (mlO$_2$·kg^{-1}) is the equivalent in O_2 of **a 1** mmol·L^{-1} of [Lac] according to di Prampero (1981). Thus the estimated contribution (in %) of anaerobic metabolism (EsC$_{ANA}$) was calculated as follows:

$$EsC_{ANA} = (O_2Eq[Lac] / \dot{V}O_2) \times 100$$

Thus, for the first 100-m the contribution of anaerobic metabolism was calculated as:

$$EsC_{ANA} = (\Delta[Lac] \times 3.1 / [(\dot{V}O_2 - \dot{V}O_{2B}) \times (t - 0.5)]) \times 100 \tag{7}$$

And it was calculated as the following for the other 100-m:

$$EsC_{ANA} = (\Delta[Lac] \times 3.1 / [(\dot{V}O_2 - \dot{V}O_{2B}) \times t] \times 100 \qquad (8)$$

The estimated contribution of aerobic metabolism (EsC_{AERO}) was the difference between total energy output and EsC_{ANA}: $EsC_{AERO} = 100 - EsC_{ANA}$.

STATISTICS

Results were presented as means ± standard deviation. Differences between measured values at the end of each test were calculated using a Wilcoxon test. Correlations between the different variables were calculated using a Pearson test. The level of significance was set at 0.05.

Results

METABOLIC PARAMETERS OF THE FOUR TESTS

The subjects swam the 400-m event in 256 s (±7 s) and their mean $\dot{V}O_2$ at the end of the 400-m was 67.2 ± 5.6 $mlO_2 \cdot kg^{-1} \cdot min^{-1}$ (Figure 1). Basal oxygen uptake ($\dot{V}O_{2B}$) and blood lactate concentration ($[Lac]_B$) before each test were not signifi-
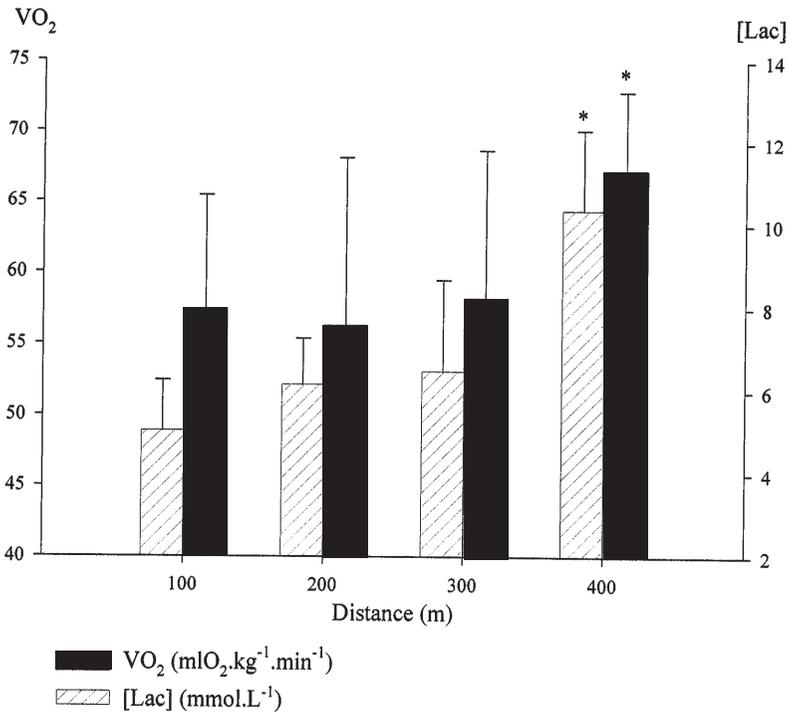

Figure 1. Changes in blood lactate concentration and $\dot{V}O_2$ at each test. *Significantly different from previous 100-m.

Table 1 Technical Parameters During the 400-m Continuously Measured, and Metabolic Parameters Measured After Each Test

	100-m	200-m	300-m	400-m
V (m·s^{-1}) per test	1.67 ± 0.05*	1.60 ± 0.04	1.57 ± 0.05	1.56 ± 0.04
V (m·s^{-1}) per 100-m	1.67 ± 0.05*	1.53 ± 0.05	1.52 ± 0.05	1.55 ± 0.05
ΔV	–	–0.14 ± 0.05	–0.01 ± 0.02	0.03 ± 0.04
SR (cycle·min^{-1})	41.6 ± 4.0**	39.2 ± 4.0	39.8 ± 4.1	41.5 ± 3.1
ΔSR (cycle·min^{-1})	–	–2.4 ± 2.74	0.6 ± 2.21	1.7 ± 2.36
SL (m·cycle^{-1})	2.43 ± 0.23+	2.36 ± 0.23	2.31 ± 0.25	2.25 ± 0.22
ΔSL (m·cycle^{-1})	–	–0.07 ± 0.2	–0.04 ± 0.15	–0.07 ± 0.12
	100-m test	200-m test	300-m test	400-m test
$\dot{V}O_2$ (ml·kg^{-1}·min^{-1})	57.3 ± 8.1	56.3 ± 11.8	58.2 ± 10.5	67.2 ± 5.6*
[Lac] (mmol·L^{-1})	5.1 ± 1.2	6.2 ± 1.1	6.5 ± 2.2	10.4 ± 1.9*
Δ[Lac] (mmol·L^{-1})	3.7 ± 1.2**	1.1 ± 0.9	0.3 ± 1.8	3.9 ± 2.0**

Note: V = swim velocity; SR = stroke rate; SL = stroke length; $\dot{V}O_2$ = oxygen uptake; [Lac] = blood lactate concentration; ΔV, ΔSR, ΔSL, Δ[Lac] = difference in velocity, stroke rate, stroke length, or blood lactate concentration between this distance and the previous. Significantly different: *from the other 100-m; **from the 2nd and 3rd 100-m; +from the 3rd and 4th 100-m (all $p < 0.05$).

cantly different (Table 1). $\dot{V}O_2$ results of the 100-, 200-, and 300-m tests were not significantly different. However, $\dot{V}O_2$ after the 400-m test was significantly higher by 869 mlO$_2$·min^{-1} (±542 mlO$_2$·min^{-1}) compared with the 100-, 200-, and 300-m tests. Results of [Lac] were closed to those of $\dot{V}O_2$. Results of [Lac] during the 100-, 200-, and 300-m tests were not significantly different from each other, but they were significantly different compared with the 400-m test, $p < 0.05$ (Table 2). In accordance with our estimate, the contribution of anaerobic metabolism was significantly higher during the 100-m test, whereas the contribution of aerobic metabolism was lower during the 100-m test, more so than for the other tests (Table 3).

CHANGES IN VELOCITY AND STROKE TECHNIQUE

Velocity (V) decreased significantly after the first 100-m and remained stable until the end of the event (Figure 2). During the first 100-m, V was significantly higher, $p < 0.05$, than it was for the next 100-m (Table 2). Stroke rate (SR) decreased significantly after the first 100-m, then increased until the end (Figure 2). During the last 100-m, SR was close to the values of the first 100-m. Thus, SR was significantly higher during the first 100-m than during the second and third 100-m, $p < 0.05$ (Table 2). Stroke length (SL) decreased all along the 400-m (Figure 2). SL was significantly higher during the first 100-m than during the two last 100-m

Table 2   Comparison of the Time, SR, [Lac]$_B$, and $\dot{V}O_{2B}$ Between 400-m Test and the Other Events Based on This Previous 400-m

	Time (s)	SR	[Lac]$_B$	$\dot{V}O_{2B}$
400-m Test				
1st 100	59.8 ± 1.6*	40.5 ± 3.9	1.4 ± 0.4	6.8 ± 1.3
2nd 100	125.3 ± 3.4	38.9 ± 4.3**		
split	65.5 ± 2.2			
3rd 100	191.1 ± 5.5	40.2 ± 4.3**		
split	65.8 ± 2.2			
4th 100	255.8 ± 6.9	41.7 ± 2.8		
split	64.7 ± 2.1			
300-m Test				
1st 100	59.7 ± 1.6*	41.0 ± 5.0	1.4 ± 0.4	5.7 ± 1.5
2nd 100	125.4 ± 3.2	39.4 ± 3.8**		
3rd 100	190.6 ± 5.4	38.8 ± 3.5**		
200-m Test				
1st 100	60.5 ± 1.3*	40.5 ± 4.4	1.3 ± 0.3	6.2 ± 1.9
2nd 100	125.2 ± 3.4	39.1 ± 3.4**		
100-m Test				
1st 100	59.7 ± 1.6	42.4 ± 5.3	1.5 ± 0.6	6.2 ± 1.1

Note: SR = stroke rate (cycle·min^{-1}); [Lac]$_B$ = basal blood lactate concentration (mmol·L^{-1}); $\dot{V}O_{2B}$ = basal oxygen uptake (ml·kg^{-1}·min^{-1}). Significantly different: *from the other 100-m of each test; **from the 2nd and/or 3rd 100-m of each test (both $p < 0.05$).

Table 3   Estimated Contribution of Aerobic and Anaerobic Metabolism During Each 100-m of the 400-m Event

	100-m	200-m	300-m	400-m	Total
% Anaerobic	45.5 ± 12.1*	6.9 ± 5.4	4.7 ± 8.8	18.3 ± 10.0	18.9 ± 3.9
% Aerobic	54.5 ± 12.1*	93.1 ± 5.4	95.3 ± 8.8	81.7 ± 10.0	81.1 ± 3.9

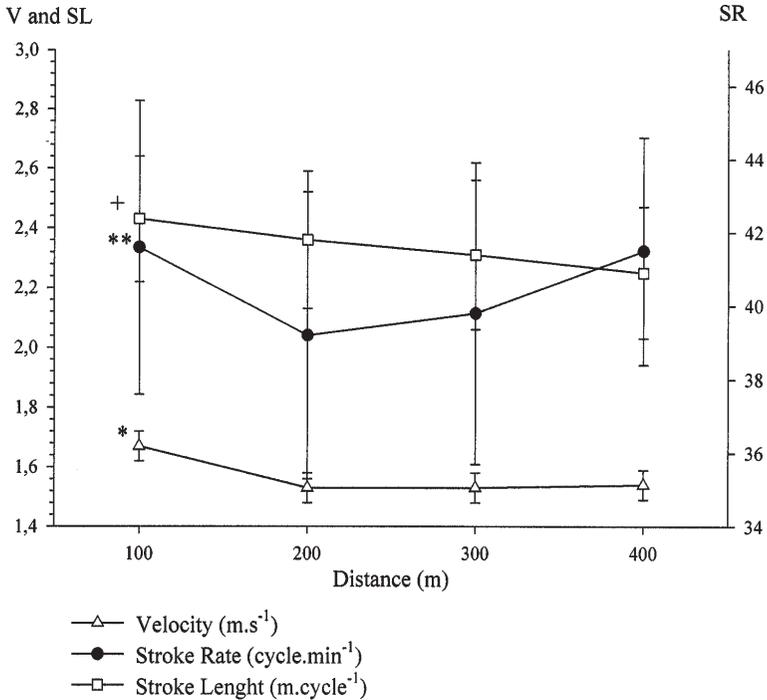*Significantly different from the other 100-m.

Figure 2. Changes in velocity, stroke length, and stroke rate during the 400-m event. Significantly different: *from the other 100-m; **from the 2nd and 3rd 100-m; [+]from the 3rd and 4th 100-m (all $p < 0.05$).

events, $p < 0.05$ (Table 2). Furthermore, V and SR of the 300-, 200-, and 100-m tests, continuously measured at each length (25 m), were never significantly different compared to the maximal 400-m event (Table 1).

CORRELATION BETWEEN STROKE TECHNIQUE AND METABOLIC PARAMETERS

SR and SL were negatively interrelated throughout the 400-m ($r = –0.95$; $p < 0.01$). The differences in V and SL between the first and second 100-m and between the second and third 100-m were significantly interrelated ($r = 0.67$; $r = 0.89$; $p < 0.05$). The difference in V and SR between the third and the fourth 100-m was positively correlated ($r = 0.77$; $p < 0.05$). A nonsignificant tendency was found between the mean V and the total decrease in SL during the 400-m event, which could suggest that faster swimmers tend to have a smaller decrease of SL ($r = 0.63$, $p = 0.1$). $\dot{V}O_2$ was not significantly correlated with the mean velocity of the 400-m. The estimated contribution of anaerobic metabolism (EsC_{ANA}) during the first 100-m was significantly higher than during the other 100-m events. Furthermore, during the second and third 100-m events, EsC_{ANA} was the lowest and sig-

nificantly lower than during the first 100-m, but then increased during the last 100-m. The mean contribution of the two metabolic pathways after the maximal 400-m event is close to one-fifth of anaerobic and four-fifths of aerobic (Table 3).

Discussion

The main results of this study were as follows: (a) The estimated contribution of anaerobic metabolism (EsC_{ANA}) represented 45% of the energy output during the first 100-m and fell during the second and third 100-m events. Furthermore, during the first and last 100-m events, the increase of EsC_{ANA} and the variations in V, SR, and SL were nonsignificantly interrelated. (b) After the first 100-m, velocity remained stable until the end of the 400-m whereas SR and SL decreased after the first 100-m, then **increased** until the end.

The aim of this study was to present a global analysis of the changes in physiological and stroke technique parameters during a maximal 400-m event conducted as if in competition. Swimmers first undertook a maximal 400-m event with the sole instruction to swim as fast as possible. No strategy was imposed on them; they chose their own stroke technique and V. It can be confirmed that swimmers swam as fast as possible at the time of the experiment, as our measurements of [Lac] were extremely close to the values of Bonifazi et al. (1993) after a 400-m race in competition (10.4 ± 1.9 vs. 11.1 ± 3 mmol·L^{-1}). The high $\dot{V}O_2$ values of the present study also support this assumption.

To follow the change in $\dot{V}O_2$ and [Lac] during the maximal 400-m event, swimmers performed three other tests based on the results of the 400-m event with 90 minutes of rest between each test. They undertook a 300-, 200-, and 100-m test, in that order, at the same velocity as the one recorded during the 400-m at each length (25 m). To guarantee better recovery, swimmers ate and drank high-energy supplements to replace the depletion of muscular glycogen stores during the test. Furthermore, the nonsignificant difference in $\dot{V}O_{2B}$ and in $[Lac]_B$, measured before each test, would suggest that swimmers recovered their initial physiological level. Therefore, for total recovery, a rest of 90 min seemed enough for well trained swimmers. The order of tests was also considered as a minor importance for performance. Thus the test order was not random, and for motivational reasons we established the order as 300-, 200-, and 100-m after the maximal 400-m event. Indeed, it seemed more logical for the swimmers to begin with the longest and hardest test and to finish with the shortest and easiest one.

Physiological data were not continuously measured during the 400-m event but rather at the end of each test. As previously discussed, the nonsignificantly different values of $\dot{V}O_{2B}$ and $[Lac]_B$ before the tests, and the nonsignificantly different values in V and SR during each test compared with the maximal 400-m, would confirm the hypothesis that the 300-, 200-, and 100-m tests were carried out in the same conditions as the 400-m event. Consequently, physiological results of the present study would be considered as the one measured at each 100-m of the 400-m event, as this event was not split into four parts. This methodology was published and validated for a track and field 400-m event (Hirvonen et al., 1992). In swimming it was first proposed by **Vilas-Boas and Duarte (1991)**. Coupled with a $\dot{V}O_2$ measurement with a breath-by-breath $\dot{V}O_2$ analyser presented by **Laffite**

and Demarle (1999) and validated by Rodriguez (2000), this methodology might be used for swimming and other activities requiring multiple measurement in $\dot{V}O_2$ and [Lac] during the event. However, this methodology provided only a global approach to the $\dot{V}O_2$ and [Lac] changes.

PHYSIOLOGICAL RESPONSES DURING MAXIMAL 400-M

The mean $\dot{V}O_2$ at the end of the 400-m event was slightly higher than the mean $\dot{V}O_2$ published by **Rodriguez (2000**) measured in the same conditions (60.3 ± 3.2 vs. 67.2 ± 5.6 mlO$_2$·kg^{-1}·min^{-1}). Maximal $\dot{V}O_2$ was reached only at the end of the 400-m event and was significantly higher than the $\dot{V}O_2$ measured at the end of the others tests. This result concurred with that of **Lavoie and Leone (1988**), who showed that $\dot{V}O_2$max can be estimated after a maximal 400-m freestyle.

A significant increase in [Lac] was observed during the first and the last 100-m. During the 200-m and 300-m tests, [Lac] remained stable and was not significantly different from the 100-m test (Figure 3). However, at the end of the 400-m event, [Lac] was significantly higher than the three previous tests and was close to the results published by Bonifazi et al. (1993). Thus, since [Lac] level provides a useful indication of energy output from glycolysis metabolism during exercise (di Prampero, 1981), we tried to estimate the contribution of the two me-
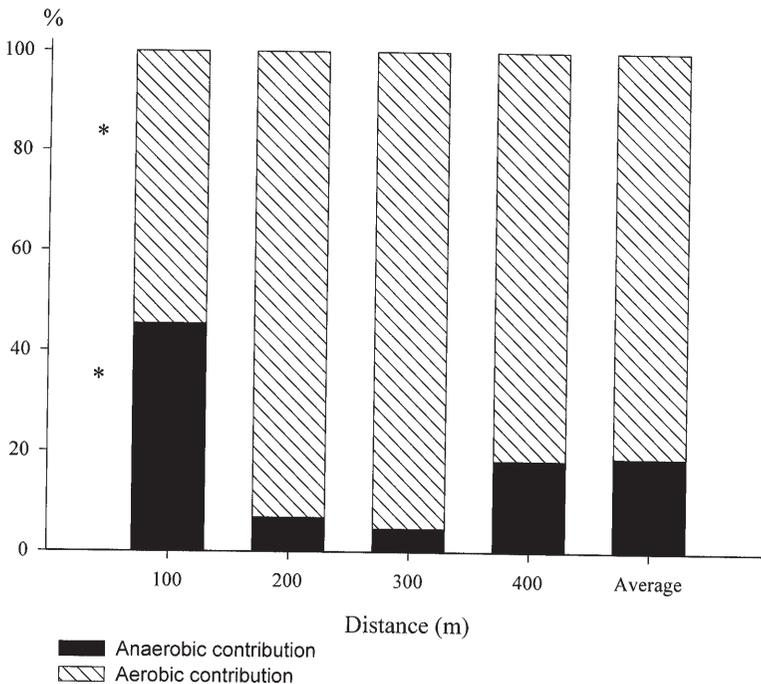

Figure 3. Estimated contribution of aerobic and anaerobic metabolism during each 100-m. *Significantly different from the other 100-m.

tabolisms during each 100-m of the 400-m event. The contribution of anaerobic metabolism (EsC$_{ANA}$) was close to 45% during the first 100-m and close to 20% during the last 100-m. However, during the second and third 100-m events, EsC$_{ANA}$ was close to 5%, and during the 400-m event EsC$_{ANA}$ was about 20%.

This result was similar to one of **Toussaint and Hollander (1994**), who showed that EsC$_{ANA}$ was close to 25% for an all-out exercise lasting about 260 s. However, through theoretical calculation, Nomura et al. (1996) found an EsC$_{ANA}$ close to 40%, representing an EsC$_{ANA}$ twofold higher than our results. This difference may stem from the changes in [Lac] during the 400-m event as found in the present study. Indeed, these particular [Lac] changes would not be expected without multiple blood lactate analysis during the 400-m, as simulated in the present study.

We found that before the 60th second of the exercise, the estimated contribution of aerobic metabolism (EsC$_{AERO}$) represented an average of only 55% of the energy output. However, between the 60th and 190th seconds of the maximal 400-m event (i.e. ,during 130 s), the aerobic system was the main energy system for ATP resynthesis and EsC$_{AERO}$, representing about 95%. However, a limit of this protocol was that the physiological data were only measured at each minute. Thus the significant changes in [Lac] or $\dot{V}O_2$ would occur before the measurement. Therefore, to refine and to give more accurate results, future studies would need to be carried out with more measurements. For $\dot{V}O_2$, this should be feasible since a breath-by-breath $\dot{V}O_2$ measurement while swimming has recently been validated (Keskinen et al., 2003).

Our first hypothesis was that swimmers were not able to maintain SL throughout the 400-m. The oxygen deficit was positively and significantly correlated with the time to exhaustion in swimming (Faina et al., 1997). Therefore, we could expect that the high contribution of anaerobic metabolism during the first 100-m would have consequences for the next 100-m. Thus the question arises as to how these potential consequences can be translated in terms of stroke technique, i.e., stroke rate or stroke length.

CHANGES IN VELOCITY AND STROKE TECHNIQUE

In the present study, V decreased significantly by 9% after the first 100-m. On the one hand, the gain of swimming start was estimated only at 3.4% of the time or 2.3% of the velocity of the first 100-m, representing a gain of about 1.5 s on the first length. On the other hand, some studies have also reported a decrease in V during the event even after the end of the effect of the dive start (Chollet et al., 1997; Desy et al., 1995; Nomura et al., 1996; Toussaint and Beek, 1992; Wakayoshi et al., 1996; Wilke, 1996; Wirtz et al., 1992). Therefore, we conclude that this change in V was not only due to overestimation in the velocity calculation, which integrated the swimming start. Thus the decrease in V after the first 100-m could be the first reflection of fatigue, which is defined as the inability to sustain velocity (Edwards et al., 1972). It may be possible that a high decrease in V was the consequence of a high EsC$_{ANA}$ of the first 100-m, although these two parameters were not correlated in the present study. This hypothesis could be verified in a future study.

It is well known that during incremental exercise without fatigue, V increases with the combination of an increase in SR and a decrease in SL (**Craig and**

Pendergast, 1982). However, Wakayoshi et al. (1996) showed that during a test of constant swimming speed, above the velocity of the onset of blood lactate accumulation (vOBLA), a swimmer must increase SR to maintain constant velocity. Furthermore, compared to velocity during free swimming, different studies showed a decline in velocity during competition, i.e., 200-m races or longer (**Craig and Pendergast, 1985; Hay and Guimaraes, 1983**). These authors found that the decline in V during these races was almost completely accounted for by the decrease of SL, given that the stroke rate remained stable as the race progressed.

Our results are in accordance with **the previous one**. Indeed, in the present study SL was significantly higher during the first 100-m compared with the other 100-m, and was lower during the last 100-m. SL decreased all along the 400-m event, and SR decreased significantly after the first 100-m, as did velocity. Thus we suggest that the decrease in SL after the first 100-m was not due to an increase in SR, since SR falls during the same time, but rather that the technical modifications were an adaptation due to physiological strain. The decrease in SL during the other 100-m is also not the consequence of an increase of SR, since velocity remained stable from the second 100-m until the end. Thus it seems that during high intensity all-out exercise, as in competition conditions, the decrease in SL is inevitable regardless of the competitor's level, and consequently, in order to maintain the highest velocity, the swimmers increase SR to compensate for the decrease in SL. **Craig and Pendergast (1985**) showed that the faster swimmers compensated for the decrease in SL by maintaining or increasing SR more than the slower competitors. This was not observed in the present study, possibly because of the homogeneity of the swimmers.

Craig and Pendergast (1985) also showed that during the 400-m freestyle in a competitive event, elite male swimmers can increase velocity in the last 100-m of the race by increasing SR, while minimizing the decrease in SL. In the present study a **nonsignificant tendency** was found between the mean V and the total decrease in SL during the 400-m event, which could suggest that faster swimmers tend to have a smaller decrease in SL. However, for **Toussaint and Beek (1992**), since SL is not only related to propelling efficiency but also to work per stroke, it is not surprising that during a race the SL decreases. Thus they hypothesized that the decrease in SL during races other than sprint events may be a reflection of a diminishing capacity to deliver power output, and perhaps also, of "non-optimal power output distribution." This last hypothesis was also submitted earlier by di Prampero et al. (1974): with fatigue, swimmers may pay less attention to body alignment, which increases drag and consequently induces a decrease in SL.

Conclusion

This study showed that the swimmers were not able to maintain stable SL throughout the maximal 400-m freestyle event. Thus, to maintain stable velocity and to compensate for the decrease in SL, swimmers increased SR during the last 300-m. Furthermore, the mean estimated contributions of aerobic and anaerobic metabolism during the maximal 400-m event were about 80% and 20%, respectively. However, we suggested that the high EsC_{ANA} during the first 100-m may have caused the higher fall in SR and SL after the first 100-m.

Acknowledgments

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