

Kick frequency affects the energy cost of aquatic locomotion in elite monofin swimmers

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Abstract The aim of this study was to evaluate the influence of kick frequency (K_F) on the energy cost of aquatic locomotion in elite monofin (Mf) swimmers at the surface. Eight subjects of international calibre (4 females, 4 males) were requested to perform in a 50-m outdoor swimming pool: (1) a continuous multi-stage incremental test to determine maximal physiological responses and (2) a submaximal exercise composed of five constant Mf-swimming tests (600-m exercise, 5-min rest) at an intensity corresponding to 90% of the velocity at the maximal oxygen uptake ($\dot{V}O_{2\max}$). The first submaximal Mf-swimming test was systematically conducted at a freely chosen K_F (FCK $_F$) and the other tests were performed at FCK $_F - 15\%$, FCK $_F - 10\%$, FCK $_F + 10\%$ and FCK $_F + 20\%$ in a random order. No significant effect of K_F on ventilation, heart rate and blood lactate concentration was observed throughout the submaximal Mf-swimming tests. However, mean values in Ec or fraction of $\dot{V}O_{2\max}$ were

significantly lower during the FCK $_F + 10\%$ condition as compared to those observed during the FCK $_F - 15\%$ (-11.5 and -9.6% , respectively, $P < 0.05$) and FCK $_F - 10\%$ (-10.4 and -9.3% , respectively, $P < 0.05$) conditions. In conclusion, the lack of significant differences between FCK $_F + 10\%$ and FCK $_F$ or FCK $_F + 20\%$ does not allow to identify a specific trend, but suggests the occurrence of an energetically optimal K_F close to that freely chosen by the Mf swimmers. Variations in muscle activity level and active drag have been hypothesized to explain the observed differences in Ec consecutive to the selection of various K_F .

Keywords Energy cost · Aquatic locomotion · Kick frequency · Active drag · Muscle activity · Elite monofin swimmers

Introduction

As for cetaceans (whams and dolphin), undulation of the axial structures is the basis for propulsion in monofin (Mf) swimming. The characteristics of kick leg induced in Mf-swimming are traditionally compared with the dolphin movement (e.g. Nicolas et al. 2007; von Loebbecke et al. 2009). The technique of dolphin kick is continuously used during various Mf swimming distances ranging from 50 to 1,500 m in the context of pool racing and until 20 km in outdoor conditions. This kind of aquatic movement consists of simultaneously vertically oriented motions of the feet from which local forces are produced during up and down movements (Rejman 1999). To generate a propulsive force, the Mf swimmer gives acceleration to a mass of water, which acquires in return kinetic energy. Mf swimming has been mainly the subject of kinematic investigations focusing on

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the analysis of active drag, produced impulsive forces or undulation characteristics (Nicolas and Bideau 2009; Nicolas et al. 2007; Rejman 1999). Based on the swimming model (Toussaint and Truijens 2005), the Mf-swimming performance depends mainly on the capacity of the swimmer to produce a high-mechanical power output enabling the generation of high-propulsive forces while reducing both active drag and energy expenditure.

As is the case for human locomotion on land, the energy cost of Mf swimming (i.e. the energy expenditure to cover one unit distance at a required speed, E_c), depends on the mechanical work produced by muscles to maintain a given speed. Using a model of energy conversion specific to aquatic locomotion (Daniel 1991), a number of parameters may affect this mechanical work and thereby, the overall performance in high level Mf swimming. Within this framework, a great part of the energy expenditure is utilized to contribute to useful thrust and to overcome active drag, which may be considered as one of external components influencing aquatic performance (di Prampero et al. 1974; Nicolas et al. 2007). Recently, Nicolas and Bideau (2009) have shown that active drag was significantly higher at the surface compared to the underwater Mf swimming, suggesting an increase in E_c to overcome hydrodynamic resistances when Mf swimmers practice at the surface.

Data concerning the relationship between E_c and swimming with fins are scarce in the literature and refer mainly to underwater and surface experiments that focus on the differences in E_c of swimming at different depths (Morrison 1973), speeds (Zamparo et al. 2002, 2006) or with different physical characteristics such as Mf, small-flexible and large-stiff fins at the surface (Zamparo et al. 2006). Most of these studies have reported that these different variables modify active body drag and affect the E_c of fin or Mf swimming. Zamparo et al. (2002) have also indicated that the speed of muscular contraction characterized by the variations in kick frequency (K_F) constitutes a parameter affecting E_c during swimming with fins. More specifically, given that active drag is particularly increased with vertical motion of the Mf at the surface compared to underwater conditions (Nicolas and Bideau 2009), one of the variables on which Mf swimmers can play is the selection of K_F in an attempt to optimize E_c . The large variations of K_F may affect the propelling characteristics (i.e. vertical amplitude) at the surface (Nicolas et al. 2007) and thereby, active drag and E_c for a given speed. In comparison with cyclic terrestrial activities, the specific analysis of the relationship between the movement pattern and E_c is missing in the context of aquatic locomotion. This analysis would allow us to identify the physiological adaptations but also, to infer on kick leg strategies that may be potentially selected by elite subjects during middle and long distance Mf-swimming events. Consequently, the

evaluation of Mf swimmers based on the manipulation of dolphin kick would provide relevant theoretical and practical information for coaches and elite Mf swimmers during training and racing exercises.

Therefore, the objective of this study was to evaluate the effect of K_F on the E_c of aquatic locomotion at a sub-maximal intensity in Mf swimmers of international calibre. Based on the previous biomechanical reports, we hypothesized that the selection of high compared to low K_F reduces active drag (by decreased vertical amplitude of the Mf) and thereby, the E_c of Mf-swimming exercise.

Materials and methods

Subjects

Eight well-trained Mf swimmers (4 males and 4 females) who were all members of the French elite national Mf-swimming team participated in this study. These athletes (mean age 18 ± 2.5 years; mean weight 70.5 ± 9.0 kg; mean height 171.0 ± 8.8 cm) were subjected to a twice daily training (from 1.5 at 2 h by session), corresponding to a mileage and hourly volume of $60\text{--}65$ km week⁻¹ and $20\text{--}22$ h week⁻¹. Best performances obtained during the official 1,500-m distance in our subjects to national and international competitions were ranged from 12 min 44 s to 13 min 35 s for male and from 13 min 57 s to 14 min 24 s for female. Mf swimmers gave their informed written consent to participate in the current study, which has been conducted according to the Declaration of Helsinki. A local ethics committee for the protection of individuals gave approval concerning the project before its initiation.

Overview

Following a standardized warm-up of 1,200 m, each athlete completed two experimental sessions in a 50-m outdoor swimming pool separated by a rest period at least 24 h. To minimize possible influence of the circadian rhythm, subjects performed Mf-swimming tests at the same time of day. During these sessions, the water temperature was nearly 27°C and the outdoor temperature was ranged from 10 to 15°C. The first session consisted of a continuous multi-stage incremental test for determination of maximal physiological and kinematic parameters. During the second session, subjects were requested to perform a submaximal Mf-swimming exercise at intensity close to the training context and using different K_F . All subjects were asked to replicate the technique of dolphin kick while using the same training Mf during the two experimental sessions. Subjects were instructed to perform an open turn, always performed to the same lateral wall side without streamline

in order to allow easily the measurements of physiological parameters.

Maximal and submaximal Mf-swimming exercises

The continuous multistage incremental Mf test started at a velocity of 1.10 m s^{-1} with an increment of 0.10 m s^{-1} for females and 0.15 m s^{-1} for males each 200-m step until exhaustion for determination of maximal oxygen uptake ($\dot{V}O_{2\text{max}}$), maximal heart rate (HR_{max}), maximal blood lactate concentration ($[La_{b\text{max}}]$), maximal ventilation ($\dot{V}E$), maximal respiratory exchange ratio (R_{max}) and Mf-swimming velocity associated with $\dot{V}O_{2\text{max}}$ ($v\dot{V}O_{2\text{max}}$). During this test, Mf-swimming velocity for each 200-m step was imposed by an operator walking on the side of the pool at the preset pace. Markers spaced by 5 m were laid out on the pool deck, and the corresponding split times were provided to the operator. The subject was asked to maintain pace by keeping their elbow at approximately 20 cm from the subaquatic visual marker controlled by an operator walking on the deck. Subjects were instructed to maintain the arms hyper extended over the head. The end of the Mf-swimming bout was dictated by the inability of subjects to maintain the required velocity and thereby, to keep the imposed distance with the subaquatic visual pacer (i.e. 0–30 cm interval).

Subsequently, subjects performed a submaximal exercise composed of five Mf-swimming tests (600-m exercise, 5-min rest) at a constant velocity of $90\% v\dot{V}O_{2\text{max}}$. This exercise intensity was chosen to replicate those currently selected by elite Mf swimmers during training sessions. The first Mf-swimming test was systematically conducted at a freely chosen K_F (FCK_F). Afterwards, subjects requested to swim at two low K_F (i.e. $FCK_F - 15\%$ and $FCK_F - 10\%$) and two high K_F ($FCK_F + 10\%$ and $FCK_F + 20\%$) in a random order (Fig. 1). The $FCK_F - 15\%$, bout did constitute the lowest K_F imposed in

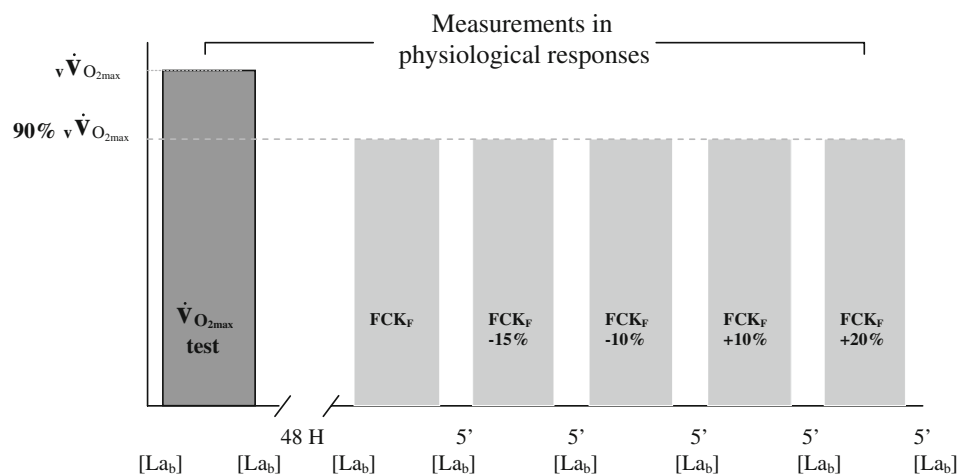
our subjects to maintain the required Mf-swimming intensity. An aqua-metronome (Finis Tempo Trainer) placed under the swimming cap of each subject was programmed to emit an audio signal at a given K_F . During this session, Mf-swimming velocity for each submaximal test was imposed using the same methodological criteria selected during the incremental test.

Measurements in physiological parameters

During all experimental sessions, gaz and respiratory exchanges were measured breath-by-breath using a portable system (K_4b^2 ; Cosmed, Rome) previously validated by McLaughlin et al. (2001). The K_4b^2 was connected to a snorkel (Aquatrainer®; Cosmed) previously used in the swimming evaluation so that an athlete can perform aquatic activity without restriction, and breath-by-breath measurements can be recorded during exercise (e.g. Roels et al. 2005, 2006). This new system only uses the expiratory flow and calculates gas exchange differently than systems previously validated by Keskinen et al. (2003) and used to evaluate highly trained swimmers (e.g. Barbosa et al. 2006; Fernandes et al. 2008). Therefore, due to the technical characteristics of our system, the results of the current study should be compared with the literature with caution.

In our work, breath-by-breath $\dot{V}O_2$ data obtained during all exercise trials were first smoothed with a five-breath moving average filter to reduce signal noise or artefacts and, secondly analyzed during the overall last 2 min of each Mf-swimming condition. The K_4b^2 was calibrated immediately prior to the exercise testing of each subject according to the specifications of the manufacturer. The 5% CO_2 and 15% O_2 gas used for the calibration of the criterion gas analysers was used to set the span for the portable unit, and the flowmeter of the K_4b^2 was calibrated using a 3.00-l syringe (Hans-Rudolph Inc., Kansas City, MO). The global calibration of Cosmed K_4b^2 (gas of ambient air/

Fig. 1 Graphic representation of the Mf-swimming tests. $[La_b]$: analysis of blood lactate concentration



references gas/delay and volume) was performed systematically near the outdoor pool and for each subject. The turbine of the flowmeter and capillary tube (Permapure) which may be sensitive to aquatic environment were replaced for each subject and one calibration of gas (ambient air) was systematically conducted during the recovery period (5 min) occurring between the K_F conditions.

HR values were monitored using a polar unit (RS400, Polar®, Kempele, Finland) during the Mf-swimming exercises. $\dot{V}O_{2\max}$ was determined according to the traditional physiological criteria (Howley et al. 1995): occurrence of a plateau in $\dot{V}O_2$, despite an increase in Mf-swimming velocity, elevated in respiratory exchange ratio ($R \geq 1.0$) or an HR over 90% of the predicted maximal HR. Breath-by-breath data were reduced to 10 s averages and the four highest consecutive $\dot{V}O_2$ values were summed to determine $\dot{V}O_{2\max}$. During the submaximal exercise, the energy cost (Ec, in $J m^{-1}$) of Mf swimming was calculated by dividing mean $\dot{V}O_2$ by mean speed (di Prampero 1986). The physiological parameters were averaged during the last 2 min of each Mf-swimming exercise. The blood lactate concentration [La_b] was obtained using a Lactate Pro® analyser (Akray, Kyoto, Japan), previously validated by Pyne et al. (2000), from 5- μ L samples of blood taken from the earlobe at rest and 3 min after the maximal exercise but also, 3 min consecutive to each recovery period of submaximal Mf-swimming tests.

Measurements in kinematic parameters

During the maximal and submaximal exercises, the kinematic parameters were measured using a PC software recently used in the analysis of stroking characteristics in trained swimmers (Alberty et al. 2009). Using that software, the swimming time per pool length (s) was measured. The swimming velocity (V , $m s^{-1}$) was then calculated. The K_F (in hertz, Hz) was measured cycle by cycle during the heel crossing with the water surface during the overall Mf-swimming exercise. Finally, the horizontal displacement during an undulation cycle (Hdc, $m cycle^{-1}$) was calculated as the ratio between V and K_F . For each submaximal test, the corresponding values of K_F , Hdc and V were continuously recorded and mean values in these variables were obtained from the overall time of exercise.

Statistical analysis

All values are expressed as mean (standard deviation). After analysis of normality and homogeneity of variance of the tested samples, differences in fraction of $\dot{V}O_{2\max}$ ($F\dot{V}O_{2\max}$), Ec, $\dot{V}E$, R , HR and [La_b] values were analyzed between the five submaximal Mf-swimming tests (i.e. FCK_F , $FCK_F - 15\%$; $FCK_F - 10\%$; $FCK_F + 10\%$;

$FCK_F + 20\%$) using an one-way analysis of variance with repeated measures. For this analysis, the $F\dot{V}O_{2\max}$ (%) were analyzed by an arcsine transformation. Subsequently, the Tukey's post hoc analysis was applied to determine significant differences over each submaximal test. Statistical significance was established at a level of $P < 0.05$.

Results

Mean values for $\dot{V}O_{2\max}$, HR_{\max} , [$La_{b\max}$], $\dot{V}E_{\max}$ and R_{\max} obtained from all eight Mf swimmers are shown in Table 1. The mean values in K_F , Hdc and V observed during the incremental Mf-swimming test were, respectively, 0.99 (0.2) Hz, 1.59 (0.1) $m cycle^{-1}$ and 1.57 (0.2) $m s^{-1}$. No significant change in HR, $\dot{V}E$, R and [La_b] values was found between the tests conducted at different K_F . However, during the submaximal exercise, the statistical analysis indicates an effect of K_F modality on mean Ec (Table 2) and $F\dot{V}O_{2\max}$ (Fig. 2) characterized by significant lower mean values in these variables at $FCK_F + 10\%$ as compared to the $FCK_F - 10\%$ (-10.4 and -9.3% , respectively, $P < 0.05$) and $FCK_F - 15\%$ (-11.5 and -9.6% , respectively, $P < 0.05$) tests. Mean K_F and Hdc values were 0.79, 0.68, 0.72, 0.87, 0.94 Hz and 1.74, 1.99, 1.81, 1.73, 1.60 $m cycle^{-1}$ during the FCK_F , $FCK_F - 15\%$, $FCK_F - 10\%$, $FCK_F + 10\%$ and $FCK_F + 20\%$, respectively. Mean values in V were, respectively, 1.42, 1.41, 1.42, 1.42 and 1.43 $m s^{-1}$ during the FCK_F , $FCK_F - 15\%$, $FCK_F - 10\%$, $FCK_F + 10\%$ and $FCK_F + 20\%$. The measured velocity–theoretical velocity ratio but also, the measured K_F –theoretical K_F ratio were calculated during the submaximal K_F tests and presented in Table 3.

Discussion

The objective of the present study was to evaluate specifically the influence of K_F on Ec in elite Mf swimmers at the surface. Our results are partially in agreement with our hypothesis, indicating a significant decrease in the mean Ec

Table 1 Physiological responses induced during the incremental Mf-swimming session

Parameters	
$\dot{V}O_{2\max}$ ($L min^{-1}$)	2.98 (0.51)
$\dot{V}O_{2\max}$ ($ml min^{-1} kg^{-1}$)	42.6 (6.9)
HR_{\max} (bpm)	189.0 (1.9)
[$La_{b\max}$] ($mmol L^{-1}$)	6.5 (1.9)
R_{\max}	1.10 (0.10)
$\dot{V}E_{\max}$ ($L min^{-1}$)	104.2 (22.2)

Table 2 Physiological responses during the submaximal Mf-swimming tests conducted at $FCK_F - 15\%$, $FCK_F - 10\%$, FCK_F , $FCK_F + 10\%$ and $FCK_F + 20\%$

Parameters	$FCK_F - 15\%$	$FCK_F - 10\%$	FCK_F	$FCK_F + 10\%$	$FCK_F + 20\%$
$\dot{V}O_2$ (L min ⁻¹)	2.42 (0.59)	2.42 (0.57)	2.35 (0.53)	2.19 (0.41) ^a	2.31 (0.38)
Ec (J m ⁻¹)	590.3 (113.1)	584.8 (106.3)	573.4 (104.2)	529.4 (71.9) ^a	551.8 (67.2)
HR (bpm)	158.3 (13.6)	159.3 (13.3)	154.1 (15.6)	154.6 (10.8)	156.2 (16.0)
[La _b] (mmol L ⁻¹)	2.30 (0.87)	2.18 (0.85)	1.80 (0.67)	1.77 (0.71)	1.92 (0.76)
R	0.97 (0.04)	0.94 (0.04)	1.00 (0.06)	0.95 (0.05)	0.93 (0.09)
$\dot{V}E$ (L min ⁻¹)	66.4 (15.7)	64.6 (14.8)	68.2 (20.7)	61.4 (14.9)	63.9 (14.1)

^a Significantly different from the $FCK_F - 15\%$ and $FCK_F - 10\%$ tests

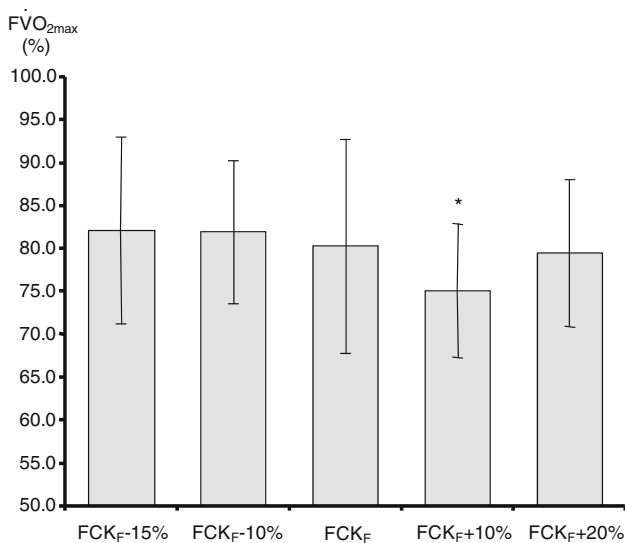


Fig. 2 Changes in fraction of $\dot{V}O_{2max}$ ($F\dot{V}O_{2max}$, in %) during the submaximal Mf-swimming tests conducted at $FCK_F - 15\%$, $FCK_F - 10\%$, FCK_F , $FCK_F + 10\%$ and $FCK_F + 20\%$. *Significantly different from the $FCK_F - 15\%$ and $FCK_F - 10\%$ tests

Table 3 Ratio between mean values in speed and frequency measured and theoretical obtained during the submaximal Mf-swimming tests at $FCK_F - 15\%$, $FCK_F - 10\%$, FCK_F , $FCK_F + 10\%$ and $FCK_F + 20\%$

	Measured speed/ theoretical speed (%)	Measured frequency/ theoretical frequency (%)
$FCK_F - 15\%$	99.5 (2.2)	103.6 (4.1)
$FCK_F - 10\%$	100.0 (2.0)	101.8 (2.5)
FCK_F	100.4 (2.7)	100.0 (3.5)
$FCK_F + 10\%$	100.2 (2.1)	98.5 (2.4)
$FCK_F + 20\%$	100.2 (2.0)	98.0 (2.1)

value only during the $FCK_F + 10\%$ session as compared to that obtained during the low K_F conditions. The variations in level of muscular activity and active drag linked to the K_F selection have been hypothesized to account for the differences in Ec values observed between the submaximal tests. The current findings provide valuable and practical

information on potential strategies of kicking pattern selected by Mf swimmers in an attempt to reduce energy demand for velocities close to those induced during middle and long distances (e.g. from 1,500 to 6,000 m).

Data on Mf swimming are scarce and refer to underwater and surface experiments that focus mainly on the kinematic evaluation of the dolphin kick (Rejman 1999; Rejman and Ochmann 2007), the measurement of active drag (Nicolas and Bideau 2009; Nicolas et al. 2007) or the analysis of Ec using different physical characteristics of fins (Zamparo et al. 2006). Independently of Mf physical characteristics, Nicolas et al. (2007) have suggested that the variable on which elite Mf swimmers can work for improving performance was the frequency of movement which may be adjusted to satisfy the metabolic energy requirement in relation with the task constraints (i.e. intensity and exercise duration). Our investigation is the first to measure specifically the Ec responses in elite Mf swimmers at the surface for velocities close to those currently used during training sessions ($>1.4 \text{ m s}^{-1}$). The mean values of $\dot{V}O_2$ (74–82% $\dot{V}O_{2max}$, Fig. 2), HR (81–84% HR_{max}) and [La_b] (27–35% [La_{bmax}]) indicate the predominance of aerobic pathway and valid the evaluation of aquatic locomotion from the Ec calculation (e.g. Daniel 1991; di Prampero 1986). The most interesting findings are linked to the differences in Ec between the K_F conditions, indicating a significant decrease in Ec at $FCK_F + 10\%$ as compared to that observed during the $FCK_F - 15\%$ and $FCK_F - 10\%$ conditions. The lack of significant differences between $FCK_F + 10\%$ and FCK_F or $FCK_F + 20\%$ does not allow to identify a specific trend (e.g. the higher K_F the lower E_C), but suggests the occurrence of an energetically optimal K_F (for a given Mf-swimming velocity) close to that freely chosen by the Mf swimmers.

Furthermore, Zamparo et al. (2006) have demonstrated that the Ec value was a function of K_F selection for lower Mf velocities comprising between 0.8 and 1.1 m s^{-1} . At variance with our study, the Mf velocity selected by these authors was not constant, but increased throughout experimental sessions. Therefore, the Ec responses to K_F

variations observed in our study are not comparable with those previously published and indicate that the $FCK_F + 10\%$ condition constitutes the best compromise between K_F and H_{dc} to optimize the production of propulsive forces and the associated energy demand at a constant Mf velocity $>1.40 \text{ m s}^{-1}$. Several hypotheses may be advanced to explain the increase in E_c responses observed during the conditions conducted at low K_F as compared to the $FCK_F + 10\%$ session. In our study, the increase in E_c values observed at low K_F conditions as compared to the $FCK_F + 10\%$ session might result, in part, in a higher variation in muscular activation to produce the propulsive force at a given Mf velocity. Based on a biomechanical analysis of Mf swimming, interesting findings have indicated the occurrence of an inversely proportional relation between the force of sagging of the Mf surface in reaction to active drag and the movement frequency (Rejman 1999). Similarly, the data obtained from the cycling literature demonstrate an increase in force applied to the cranks with decreasing pedal rate (e.g. Patterson and Moreno 1990). In this context, Ahlquist et al. (1992) have previously reported that an increased muscle force required to meet the higher resistance per cycle at a low pedal rate (50 rpm) resulted in greater type II fibers glycogen depletion. The supplementation of type I by type II fibers would be linked to a decrease in thermodynamic muscle efficiency leading to an increase in E_c parameter (Woledge 1998). When considering these reports, the selection of low K_F might induce an increase in the force applied to the Mf to overcome active drag, contributing to the additional recruitment of type II fibers and the increased $\dot{V}O_2$. Nonetheless, the EMG activity to infer on the muscle fibers recruitment of quadriceps (involved greatly during the dolphin kick) and reaction forces generated by the Mf have not been measured in our study. Although the EMG analysis remains complex in the water (due to the elevated signal noise), this constitutes an important limitation of our investigation and makes it difficult to analyse $\dot{V}O_2$ responses to K_F variations.

In swimming, Demarie et al. (2001) have suggested that the increase in $\dot{V}O_2$ observed during a 6-min heavy exercise was linked partially to the alteration of pulmonary function. When the athlete is immersed in the water, the respiratory work may be more elevated to overcome the force of hydrostatic pressure exerted on the thoracic cage (Ogita and Tabata 1992). Based on these data, the ventilation cost of Mf swimming might be more influenced by the selection of low K_F generating a higher active drag and affect specifically the E_c value during the submaximal tests. The lack of significant change in mean V_E values between the Mf-swimming tests (Table 2) suggests that the ventilation cost of Mf-swimming remains stable throughout the submaximal sessions and cannot be taken into

consideration in the analysis of the E_c increase observed at low K_F conditions. Complementary data from the biomechanical evaluation of Mf swimming may be used in an attempt to explain the variations in E_c between the submaximal tests.

As is the case for human locomotion on land, the E_c of aquatic locomotion depends on the mechanical work produced by muscles to sustain a given forward velocity. This mechanical work is generally partitioned into two major components: the external work and the internal work (e.g. Fenn 1930). The external work is mainly characterized by the great part of the metabolic energy which is utilized to overcome active drag (di Prampero et al. 1974). Indeed, Nicolas et al. (2007) suggested that the Mf-swimming performance depends on the capacity of the subject to produce high-propulsive forces while reducing both active drag and associated expenditure energy. Several factors may be hypothesized to affect active drag during Mf swimming, such as the characteristics of undulation. It has been shown an increased active drag with vertical excursion of the Mf in elite Mf swimmers (Nicolas and Bideau 2009; Nicolas et al. 2007). These authors have reported that greater vertical amplitude leads to a larger effective cross-sectional area inducing probably more drag. One of factors on which Mf swimmers may play in an attempt to modify the vertical amplitude of the Mf and active drag is the K_F selection (Nicolas et al. 2007). This attractive hypothesis is in agreement with the results by Arellano et al. (2003), indicating that swimmers practising the dolphin kick increase their K_F and decrease their amplitude for improving the forward velocity during underwater testing bouts. Considering these previous statements, we hypothesize that the selection of low K_F as compared to the $FCK_F + 10\%$ condition induces a higher vertical motion of the Mf which, in return, increases active drag and the associated energy expenditure necessary to produce the required velocity. Given the lack of kinematic measurements in our study, it would be interesting, in a future investigation, to verify specifically the vertical amplitude of the Mf and wave speed (using the video analysis) to K_F variations but also to measure active drag produced during each K_F condition.

Conclusion

Findings of this study indicate that the selection of K_F exerts an influence on the E_c response and constitutes a determinant of Mf-swimming energetics during submaximal intensities. The $FCK_F + 10\%$ condition is associated with a significant reduction in E_c values as compared to the $FCK_F - 15\%$ and $FCK_F - 10\%$ conditions and seems to be the best combination between frequency and kick

amplitude to optimize the E_c at high velocities. Our results suggest that internal and external mechanisms, such as changes in muscular activity and active drag, probably contribute to the effects of K_F variations on E_c responses. Further investigations based on a holistic approach including biomechanical and physiological measurements are necessary to investigate the influence of K_F on the E_c in the context of Mf-swimming performance.

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