©Journal of Sports Science and Medicine (2014) **13,** 610-615
http://www.jssm.org

Research article

Kinematical Analysis along Maximal Lactate Steady State Swimming Intensity

Pedro Figueiredo [1], Rafael Nazario [1], Marisa Sousa [1], Jailton Gregório Pelarigo [1], João Paulo Vilas-Boas [1,2] and Ricardo Fernandes [1,2] ✉
[1] Centre of Research, Education, Innovation and Intervention in Sport of the Faculty of Sport of the University of Porto;
[2] Porto Biomechanics Laboratory (LABIOMEP), University of Porto, Porto, Portugal

Abstract

The purpose of this study was to conduct a kinematical analysis during swimming at the intensity corresponding to maximal lactate steady state (MLSS). Thirteen long distance swimmers performed, in different days, an intermittent incremental protocol of n x 200 m until exhaustion and two to four 30-min submaximal constant speed bouts to determine the MLSS. The video analysis, using APAS System (Ariel Dynamics Inc., USA), allowed determining the following relevant swimming determinants (in five moments of the 30-min test: 0, 25, 50, 75, and 100%): stroke rate, stroke length, trunk incline, intracyclic velocity variation, propelling efficiency, index of coordination and the time allotted to propulsion per distance unit. An ANOVA for repeated measures was used to compare the parameters mean values along each moment of analysis. Stoke rate tended to increase and stroke length to decrease along the test; a tendency to decrease was also found for intracyclic velocity variation and propelling efficiency whereas the index of coordination and the propulsive impulse remained stable during the MLSS test. It can be concluded that the MLSS is not only an intensity to maintain without a significant increase of blood lactate concentration, but a concomitant stability for some biomechanical parameters exists (after an initial adaptation). However, efficiency indicators seem to be more sensitive to changes occurring during swimming at this threshold intensity.

Key words: Swimming, front crawl, biomechanics, aerobic capacity, lactate.

Introduction

Swimming is an individual and cyclic sport influenced by several determinant factors (Barbosa et al., 2010). From these, biomechanical and energetic related parameters are the most relevant, whose developments allow significantly enhancing performance and achieving high-standard competitive levels. The useful mechanical power in swimming is that to overcome drag forces ($\dot{W}_d = D \times v$) and, since metabolic power ($\dot{E}$) is related to this component of total mechanical power through the drag efficiency ($\eta_d = \dot{W}_d / \dot{E}$), swimming velocity is then determined by (eg. di Prampero et al., 2011; Zamparo et al., 2011):

$$v = \dot{E} \times (\eta_d / D) \qquad (1)$$

This equation indicates that swimming velocity will be higher the highest the propelling efficiency and/or the metabolic power are, and the lower the hydrodynamic drag is.

Parameters representing each one of the above mentioned areas should be frequently monitored, aiming to develop better training processes and, therefore, increasing performance. Indeed, tests are used as part of elite training programs to assess the likely outcome of the swimmers competitive performance (Anderson et al., 2008). From these, one of the most well-known is the Maximal Lactate Steady State (MLSS) test, which aims to assess the highest workload that can be maintained over time with stable blood lactate concentration values ([La$^-$]), i.e., without a continuous blood lactate accumulation (Beneke, 1995; Heck et al., 1985). The MLSS test is considered the gold-standard protocol for assessing swimmers' individual anaerobic threshold (Beneke and Von Dullivard, 1996) and, therefore, to evaluate and prescribe individualized aerobic training.

Complementarily, the definition of training loads should focus not only on volume, intensity and frequency of training, but also on technical constraints, which would enable to control the swimmers' technique. Changes in the stroke parameters partly depend on the aerobic potential (particularly on aerobic capacity) and the extent to which the anaerobic metabolism is involved in total energy release also has a decisive role (Pelayo et al., 2007). Moreover, long distance swimming (open water and long-distance triathlons) has become increasingly popular and the strategies to maintain a constant velocity during these events, aiming to maintain the metabolic equilibrium, are important to promote specific adaptations (i.e. oxidative capacity) (Pelayo et al., 2007). Nonetheless, it possibly requires a biomechanical adjustment, as peripheral fatigue may evolve during these long duration events.

In fact, it has been reported that the anaerobic threshold seems also to influence the behaviour of some biomechanical variables, as concomitant changes on some selected kinematical and coordinative parameters and [La$^-$] during incremental and constant load tests have been reported (Figueiredo et al., 2013a; Keskinen and Komi 1993; Psycharakis et al., 2008; Wakayoshi et al., 1995) This supports the idea that, in swimming, biomechanical changes could be related to metabolic effects and that the anaerobic threshold represents not only a physiological transition but also a biomechanical and coordinative boundary, coincident with a stroke length (SL) drop, and an increase in the stroke rate (SR) and index of coordination (IdC) (Figueiredo et al., 2013a; Oliveira et al., 2012). Specifically when swimming at MLSS, it was found stability in the SL, SF and IdC in national level swimmers (Dekerle et al., 2005; Pelarigo et al., 2011), but it was suggested that this could be different depending on

Received: 31 December 2012 / Accepted: 02 April 2014 / Published (online): 01 September 2014

the swimmers level as contradictory results were reported (Pelarigo et al., 2011). In fact, this analysis should go further, as swimming performance is influenced by other relevant factors, particularly the hydrodynamic drag and propulsive forces (Toussaint, 2011).

As it has been evidenced that biomechanical skills in swimming are of far greater importance for metabolic economy than in running and cycling, and that elite swimmers adopt different combinations of stroke parameters than their less proficient counterparts, we aimed to analyse the behaviour of relevant kinematical parameters when swimming at MLSS intensity. This analysis will contribute to the understanding of the main factors that influence the maintenance of the highest swimming intensity that could be supported by the aerobic energy system without a significant rise of the [La$^-$].

Methods

Thirteen long distance swimmers voluntary participated in the present study. Their main physical and training background characteristics were: 27.8 ± 10.9 years of age, 1.76 ± 0.56 m of height, 1.77 ± 0.64 m of arm span, 68.8 ± 5.6 kg of body mass, 22.22 ± 1.65 of body mass index and 5.8 ± 4.8 years of swimming competitive experience. The criterion for swimmers' participation was a performance of 360 s (or less) in the 400 m freestyle event. The local ethics committee approved the experimental procedures and all swimmers signed a written consent form in which the protocol was detailed explained.

All test sessions took place in a 25 m indoor pool, 1.90 m deep, with a water temperature of 27.5°C. A standardized warm-up, consisting primarily of 1000 m of aerobic swimming of low-to-moderate intensity, was conducted before each protocol. Using in-water starts and flip turns, each participant performed a front crawl intermittent incremental protocol of n x 200 m until exhaustion with increments of 0.05 m/s between steps and 30 s rest intervals to assess the swimming velocity corresponding to individual anaerobic threshold (Fernandes et al., 2006). The individual anaerobic threshold was determined by [La$^-$] /velocity curve modelling method, as describe previously (Fernandes et al., 2011).

After a 48 h rest interval, a MLSS test – a long distance continuous intensity test proposed by Stegmann and Kindermann (1982) and Heck et al. (1985) – was conducted in front crawl, with swimmers performing two to four 30 min bouts at different velocities with 24 h rest in-between. The swimming velocity for the first trial was established based on the individual velocity corresponding to anaerobic threshold obtained in the intermittent incremental protocol. The velocity increments (or declines) between bouts corresponded to 2.5% of the initial 30 min velocity (Pelarigo et al., 2011) and the velocity corresponding to MLSS (v@MLSS) was defined as the highest swimming velocity during which [La$^-$] increased 1 mmol·l^{-1} during the final 20 min of the test (Baron et al., 2005; Dekerle et al., 2005; Heck et al., 1985; Hein et al., 1989). The [La$^-$] corresponding to MLSS ([La$^-$] MLSS) was obtained through the mean of [La$^-$] measured at the 10th and 30th min (blood samples were also taken at rest). During both incremental and continuous tests, velocity was controlled through a visual pacer (TAR. 1.1, GBK-electronics, Aveiro, Portugal), with flashing lights on the bottom of the pool, helping swimmers to keep up the predetermined velocity.

Swimmers were videotaped in the sagittal plane using a dual-media set-up (Sony® DCR-HC42E, Nagoya, Japan) that recorded the mid-pool stroke cycles, placed 0.30 m above and below the water surface at the lateral wall of the pool, 6.78 m from the plane of movement, and 12.5 m from the starting wall. The images of both cameras were recorded independently and swimmers were monitored when passing through a specific pre-calibrated space using a calibration frame (6.3 m^2). Synchronization of the images was obtained using a pair of lights, fixed to the calibration volume, visible in the field of view of each camera (de Jesus et al., 2012). The Ariel Performance Analysis System software (Ariel Dynamics, USA) was used to analyze the kinematical parameters along the MLSS test. Nine anatomical points, (the right hip - femoral condyle - and both sides finger tips, fist, elbow and shoulder) were digitized manually and frame by frame at a frequency of 50 Hz. After a bi-dimensional reconstruction using DLT procedure (Abdel-Aziz and Karara, 1971), a low pass filter of 5Hz was used (Winter, 1990). The duration of the MLSS test was normalized to 100% and split into five parts (0, 25, 50, 75, and 100% of the 30-min test) of its total duration for the analysis of the variables along the test (0% was only considered at 75 m because swimmers did not instantly catch up with the right pace and only mid-pool non-breathing stroke cycles were considered).

The kinematical analysis consisted on the assessment of the stroke kinematics (mean velocity, SF and SL) and the absolute trunk inclination with horizontal plane (TI, as the value of the angle between the shoulder and the hip segment and the horizontal at the end of insweep of the upper limbs action, as proposed by Zamparo et al., 2009). For the efficiency estimation, it were selected the intracycle velocity variation (IVV, computed as the hip's instantaneous velocity coefficient of variation) and the upper limb's propelling efficiency (η_p, by assessing the underwater phase only, as proposed by Zamparo et al., 2005 and indicated in Equation 2).

$$\eta_p = [(v \times 0.9) / 2\pi \times SF \times l)] (2 / \pi) \qquad (2)$$

Being l the average shoulder to hand distance (the length in the vertical axis between the shoulder and the hand during the insweep phase). The velocity was multiplied by 0.9 to take into account that ~10% of forward propulsion in front crawl is produced by the lower limbs action (Zamparo et al., 2005). To assess the motor control, the index of coordination (IdC) was evaluated, measuring the lag time between the propulsive phases of each upper limb and expressing it as the percentage of the overall duration of the stroke cycle (Chollet et al., 2000). Following these authors, the propulsive phase begins with the start of the hand's backward movement until the moment where it exits from the water (pull and push phases) and the non-propulsive phase initiates with the hand water release and ends at the beginning of the propulsive phase (recovery, entry and catch phases), existing three coordination modes: (i) catch-up, when a lag time occurred between the propulsive phases of the two upper limbs (IdC < 0%); (ii) opposition, when the propulsive phase of one upper limb started when the other ended its propulsive phase (IdC = 0%); and (iii) superposition, when the propulsive phases of the upper limbs are overlapped (IdC > 0%).

In addition, the change in the duration of the propulsive impulse, which seems to be useful to estimate the time allotted by the swimmer to propulsion per lap ($T_{prop/distance}$), was estimated as indicated in Equation 3 (Alberty et al., 2009):

$$Tprop/distance = Tcycle.(100\% + 2.IdC)D/SL \quad (3)$$

where D/SL corresponds to the number of stroke cycles needed to cover the distance and IdC is the Index of Coordination.

Mean and SD were used as measures of centrality and dispersion of the studied variables. The normal Gaussian distribution of the data was verified by the Shapiro-Wilk's test and the compound symmetry (or sphericity) was checked using the Mauchley test. When the assumption of sphericity was not met, the significance of F-ratios was adjusted according to the Greenhouse–Geisser procedure when the epsilon correction factor was <0.75 or according to the Huyn–Feld procedure when the epsilon correction factor was >0.75 (Vincent, 1999). A one-way ANOVA for repeated measures was used to compare the mean values for each variable at each point of analysis (0, 25, 50, 75 and 100% of the MLSS). When a significant F-value was achieved, Bonferroni post-hoc procedure was performed to locate the pairwise differences. All statistical analysis was performed using STATA 12.1 (StataCorp, USA) and the level of statistical significance was set at $P < 0.05$. Effect size was computed with Cohen's f. It was considered a (Cohen, 1988): (i) small effect size if $0 \leq |f| \leq 0.10$; (ii) medium effect size if $0.10 < |f| \leq 0.25$ and; (iii) large effect size if $|f| > 0.25$.

Results

As it was expected, velocity remained stable along the test ($F_{(4,48)} = 0.12$, $p = 0.98$, $f < 0.01$), with a mean value of 1.06 ± 0.14 m/s, corroborated by the constant values of $[La^-]_{MLSS}$ between the 10th and 30th min (3.25 ± 1.08 vs. 3.38 ± 1.18 $mmol.l^{-1}$, respectively). However, adaptations occurred concomitantly in the SF ($F_{(4,48)} = 14.57$, $p < 0.001$, $f = 0.23$) and SL ($F_{(4,48)} = 3.12$, $p = 0.02$, $f = 0.10$) between the first and the last moment of the 30 min test (Figure 1).

Efficiency parameters changed as well, with the η_p decreasing from the 0 and 25% to the 100% of the test ($F_{(4,48)} = 3.91$, $p = 0.008$, $f = 0.14$) and the IVV diminishing from the first three moments to the last stage of the effort ($F_{(4,48)} = 3.14$, $p = 0.02$, $f = 0.26$) (Table 1). Conversely, the TI remained stable along the test ($F_{(4,48)} = 0.51$, $P = 0.73$, $f < 0.01$) and no significant effect of time on IdC ($F_{(4,48)} = 1.11$, $p = 0.36$, $f = 0.03$) and Tprop values ($F_{(4,48)} = 0.10$, $p = 0.98$, $f < 0.01$) was observed (Table 1). All swimmers adopted the catch-up arm coordination mode.

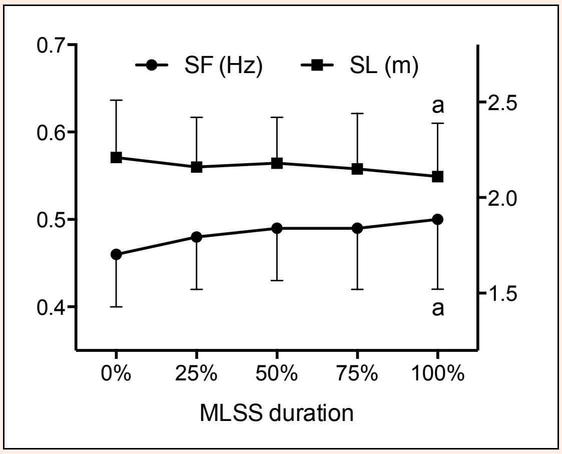

Figure 1. Evolution through MLSS test of the mean ± SD values of the stroke frequency (SF) and stroke length (SL).
^{a} Significantly different from 0% ($p < 0.05$).

Discussion

The aim of this study was to analyse the behaviour of relevant kinematical parameters when swimming at the MLSS intensity. Efficiency related parameters (IVV and η_p) and general biomechanical parameters (SF and SL) changed, but TI, IdC and Tprop remained stable along this typically aerobic effort. Moreover, the observed $[La^-]_{MLSS}$ values were similar to those reported by Dekerle et al. (2005) and Pelarigo et al. (2011) (3.30 and 3.28 $mmol.l^{-1}$, respectively), notwithstanding the differences obtained in the velocity attained at the MLSS (1.22 vs 1.06 m/s). The obtained $[La^-]$ values also evidenced, as proposed previously (Fernandes et al., 2011; Stegmann and Kindermann, 1982), that individual assessments should be used rather than averaged fixed values.

Regarding the stroking parameters, the SF and the SL values remained stable, with the exception of the 0% moment where the SF was lower and the SL higher.

Table 1. Evolution through the MLSS test of the mean (± SD) values of the trunk incline (TI), upper limb propelling efficiency (η_p), intracycle velocity variation (IVV), index of coordination (IdC) and the time allotted for propulsion per pool length (T_{prop}).

	0%	25%	50%	75%	100%
TI (°)	10.8 (3.8)	10.5 (3.9)	10.3 (3.4)	10.0 (3.9)	10.1 (3.8)
η_p	.36 (.05)	.36 (.04)	.35 (.04)	.34 (.04)	.34 (.05) ^{a,b}
IVV	.24 (.06)	.23 (.05)	.24 (.04)	.22 (.05)	.20 (.05) ^{a,b,c}
IdC (%)	-16.8 (5.8)	-15.9 (4.7)	-16.0 (5.2)	-15.6 (5.8)	-15.2 (5.0)
Tprop (s)	16.7 (4.4)	17.0 (4.3)	16.7 (4.3)	16.8 (4.0)	16.7 (3.3)

^{a,b,c} Significantly different with 0, 25, and 50%, respectively ($p < 0.05$).

These results are in agreement with Dekerle et al. (2005) and Pelarigo et al. (2011) who also reported a stability in SF and SL (but only started their analysis at 12.5% and 10th min of the test, respectively), suggesting that when beginning at MLSS intensity there is an important phase of adaptation to the imposed pace, enforcing a constancy of the required propulsion to overcome the corresponding drag impulse. However, by changing the magnitude of the generated propulsion, swimmers have some freedom in combining SF and SL.

Afterwards SF and SL remained stable, but as seen before for 400 m front crawl at an intensity corresponding to the anaerobic threshold (Keskinen and Komi, 1993) and in MLSS (Dekerle et al., 2005) studies, SF increased and SL decreased slightly and non-significantly in terms of absolute values. In addition, after a 2 km test (simulating a long-distance competition by maintaining a 10 km race pace) significant differences in SF and SL were reported (Zamparo et al., 2005). Above this intensity, at 102.5-105% (Dekerle et al., 2005; Pelarigo et al., 2011), or at the velocity of maximal oxygen consumption (Marinho et al., 2006), greater changes in SF and SL were reported, probably due to the higher technical constraints at the heavy intensity domain (above moderate exercise). This fact suggests that the maintenance of the muscular homeostasis (evidenced by the [La$^-$] stability) might be relevant for stable stroke parameters behaviour; nevertheless some peripheral fatigue may start to evolve (as observed for long distance swimming; Invernizzi et al., 2014). In addition, differences in technical skill of the swimmers could emphasize these possible changes, as it was observed that subjects with higher technical skill would be able to maintain higher SL values for longer (Chollet et al., 1997; Craig et al., 1985).

Furthermore, the TI values remained stable during the MLSS test, which might indicate that swimmers were able to maintain their swimming technique along the exercise without experiencing additional drag form, since the frontal area (highly related to the TI) is expect to be maintained (Zamparo et al., 2009). Regarding the efficiency parameters, a decrease in IVV and η_p was observed along the MLSS, in spite of the observed stability in other parameters. Nevertheless, it is known that IVV and η_p are related with the stroking parameters (Figueiredo et al., 2011; Figueiredo et al., 2013b), probably changing along the exercise due to modifications in the SF and SL. Thus, IVV and η_p seem to be more sensitive to time rather than the general stroke parameters (SF and SL), although these latter presents a tendency (in terms of absolute values) to a decrease in SL and an increase of the SF from the 1st quarter of the test till the end. In fact, η_p should not show a different trend from SL, as the ratio v/SF (equation 2) is indeed SL and all other parameters (but l) are constant. It also should be considered the fact that these variables are macro kinematical parameters, representing every adaptation that occur in face of the constraints imposed on action, resulting in the final velocity.

The task constraint of even pace should also be discussed as it could have highly influenced the initial moments of the test, rather than the eventual muscular fatigue. In fact, it is believed that the pacing selected by athletes is largely dependent on the anticipated exercise duration and on the presence of an experientially developed performance template as studies investigating pacing during prolonged exercise have observed a fast start in the beginning of race (e.g. Roelands et al., 2013). Although [La$^-$] stability was observed, swimmers could have experienced some increase in the rate of perceived exertion, profile of mood state (fatigue) and muscular pain, as observed by Invernizzi et al. (2014) for long distance swimming. In addition, the tendency to increase the SF in the final of the test may be due to a neuromuscular reserve, as evidenced for cycling exercise (Marcora et al. 2010).

Complementarily, it is known that the lower limbs action in front crawl swimming has a contribution of about 15% to overall propulsion in maximal efforts, which is considered to be low (Deschodt et al., 1999) and expected to be even lower in long distance swimming. However, as upper limb action efficiency decreased, the role of the lower limbs action may be critical and should be taken into consideration in futures studies on this topic.

The observed changes on propelling efficiency, concomitant with the SF increase, did not changed the required Tprop to overcome the drag impulse that was expected to occur due to the constant pace, without energetical increments. Alberty et al. (2009) showed that swimmers have freedom to choose the combination of SF, IdC and, consequently, Tprop. Although changes were observed in SF in the beginning of the MLSS test, they were not sufficient to impose changes on the IdC, even being a control parameter. This non-relation between SF and IdC was already reported, but during a time to exhaustion test (Alberty et al., 2009). A catch-up mode was adopted during MLSS test, remaining stable throughout, as previously observed by Pelarigo et al. (2011).

Conclusion

In summary, MLSS intensity in swimming is maintained with a concomitant stability of [La$^-$] and some biomechanical parameters (after an initial adaptation). However, efficiency indicators seem to be more sensitive to possible changes occurring through time at this intensity and should be further considered. Thus, MLSS is a useful and practical swimming intensity to be maintained for a long period of time, but some constraints in technique can occur.

References

Abdel-Aziz, Y. and Karara, H. (1971) Direct linear transformation: from comparator coordinates into object coordinates in close range photogrammetry. In: *Proceedings of the symposium on close range photogrammetry*. Church Falls, Illinois. 1-18.

Alberty, M., Sidney, M. Pelayo, P. and Toussaint, H.M. (2009) Stroking characteristics during time to exhaustion tests. *Medicine and Science in Sports and Exercise* **41(3)**, 637-644.

Anderson, M., Hopkins, W., Roberts, A. and Pyne, D. (2008) Ability of test measures to predict competitive performance in elite swimmers. *Journal of Sports Sciences* **26(2)**, 123-130.

Barbosa, T., Bragada, J., Reis, V., Marinho, D., Carvalho, C. and Silva, A.J. (2010) Energetics and biomechanics as determining factors of swimming performance: Updating the state of the art. *Journal of Science and Medicine in Sport* **13(2)**, 262-269.

Baron, B., Dekerle, J., Depretz, S., Lefevre, T. and Pelayo, P. (2005) Self-selected speed and maximal lactate steady state speed in swimming. *Journal of Sports Medicine and Physical Fitness* **45(1)**, 1-6.

Beneke, R. (1995) Anaerobic threshold, individual anaerobic threshold, and maximal lactate steady state in rowing. *Medicine and Science in Sports and Exercise* **27(6)**, 863-867.

Beneke, R. and Von Duvillard, S.P. (1996) Determination of maximal lactate steady state response in selected sports events. *Medicine and Science in Sports and Exercise* **28(2)**, 241-246.

Chollet, D., Pelayo, P., Delaplace, C., Tourny, C. and Sidney, M. (1997) Stroking characteristic variations in the 100-M freestyle for male swimmers of differing skill. *Perceptual and Motor Skills* **85(1)**, 167-177.

Chollet, D., Chalies, S. and Chatard, J.C. (2000) A new index of coordination for the crawl: Description and usefulness. *International Journal of Sports Medicine* **21(1)**, 54-59.

Cohen J. (1988) *Statistical power analysis for the behavioral sciences.* 2nd edition. Lawrence Erlbaum Associates, Hillsdale.

Craig, A.B., Skehan, P.L., Pawelczyk, J.A. and Boomer, W.L. (1985) Velocity, stroke rate, and distance per stroke during elite swimming competition. *Medicine and Science in Sports and Exercise* **17(6)**, 625-634.

de Jesus, K., de Jesus, K., Figueiredo, P.A., Gonçalves, P., Vilas-Boas, J.P. and Fernandes, R.J. (2012) Effects of Fatigue on Kinematical Parameters During Submaximal and Maximal 100-m Butterfly Bouts. *Journal of Applied Biomechanics* **28(5)**, 599-607.

Dekerle, J., Nesi, X., Lefevre, T., Depretz, S., Sidney, M., Marchand, F. H. and Pelayo, P. (2005) Stroking parameters in front crawl swimming and maximal lactate steady state speed. *International Journal of Sports Medicine* **26**, 53-58.

Deschodt, V.J., Arsac, L.M. and Rouard, A.H. (1999) Relative contribution of arms and legs in humans to propulsion in 25-m sprint front-crawl swimming. *European Journal of Applied Physiology and Occupational Physiology* **80(3)**, 192-199.

di Prampero, P.E., Pendergast, D. and Zamparo, P. (2011) Swimming economy (energy cost) and efficiency. In: *World Book of Swimming - From Science to Performance.* Eds: Seifert, L., Chollet, D. and Mujika, I.. New York: Nova Science Publishers. 297-312.

Fernandes, R.J., Billat, V.L., Cruz, A.C., Colaço, P.J., Cardoso, C.S. and Vilas-Boas, J.P. (2006) Does net energy cost of swimming affect time to exhaustion at the individual's maximal oxygen consumption velocity? *Journal of Sports Medicine and Physical Fitness* **46(3)**, 373-380.

Fernandes, R.J., Sousa, M., Machado, L. and Vilas-Boas, J.P. (2011) Step Length and Individual Anaerobic Threshold Assessment in Swimming. *International Journal of Sports Medicine* **32**, 940-946.

Figueiredo, P., Morais, P., Vilas-Boas, J.P. and Fernandes, R.J. (2013a) Changes in arm coordination and stroke parameters on transition through the lactate threshold. *European Journal of Applied Physiology* **113**, 1957-1964.

Figueiredo, P., Toussaint, H.M., Vilas-Boas, J.P. and Fernandes, R.J. (2013b) Relation between efficiency and energy cost with coordination in aquatic locomotion. *European Journal of Applied Physiology* **113(3)**, 651-659.

Figueiredo, P., Zamparo, P., Sousa, A., Vilas-Boas, J.P. and Fernandes, R.J. (2011) An energy balance of the 200 m front crawl race. *European Journal of Applied Physiology* **111(5)**, 767-777.

Heck, H., Mader, A. and Hess, G. (1985) Justification of the 4-mmol/l lactate threshold. *International Journal of Sports Medicine* **6(3)**, 117-130.

Hein, M.S., Kelly, J.M. and Zeballos, R.J. (1989) A fixed velocity swimming protocol for determination of individual anaerobic threshold. *Journal of Swimming Research* **5(3)**, 15-19.

Invernizzi, P.L., Limonta, E., Bosio, A., Scurati, R., Veicsteinas A. and Esposito, F. (2014) Effects of a 25-km trial on psychological, physiological and stroke characteristics of short- and mid-distance swimmers. *Journal of Sports Medicine and Physical Fitness* **54(1)**, 53-62.

Keskinen, K.L. and Komi, P.V. (1993) Stroking characteristics of front crawl swimming during exercise. *Journal of Applied Biomechanics* **9**, 219-226.

Marcora, S.M. and Staiano, W. (2010) The limit to exercise tolerance in humans: mind over muscle? *European Journal of Applied Physiology* **109**, 763-70.

Marinho, D.A., Vilas-Boas, J.P., Keskinen, K.L., Rodríguez, F.A., Soares, S.M., Carmo, C.M., Vilar, S.O. and Fernandes, R.J. (2006) Behaviour of the kinematic parameters during a time to exhaustion test at VO2max in elite swimmers. *Journal of Human Movement Studies* **51**, 1-10.

Oliveira, M.F., Caputo, F., Lucas, R.D., Denadai, B.S. and Greco, C.C. (2012) Physiological and stroke parameters to assess aerobic capacity in swimming. *International Journal of Sports Physiology and Performance* **7(3)**, 218-223.

Pelarigo, J.G., Denadai, B.S. and Greco, C.C. (2011) Stroke phases responses around maximal lactate steady state in front crawl. *Journal of Science and Medicine in Sport* **14(2)**, 168e1-168e5.

Pelayo, P., Alberty, M., Sidney, M., Potdevin, F. and Dekerle, J. (2007) Aerobic potential, stroke parameters, and coordination in swimming front-crawl performance. *International Journal of Sports Physiology and Performance* **2(4)**, 347-359.

Psycharakis, S.G., Cooke, C.B., Paradisis, G.P., O'Hara, J. and Phillips, G. (2008) Analysis of selected kinematic and physiological performance determinants during incremental testing in elite swimmers. *Journal of Strength and Conditioning Research* **22**, 951-957.

Roelands, B., de Koning, J., Foster, C., Hettinga, F. and Meeusen, R. (2013) Neurophysiological determinants of theoretical concepts and mechanisms involved in pacing. *Sports Medicine* **43(5)**, 301-311.

Stegmann, H. and Kindermann, W. (1982) Comparison of prolonged exercise tests at the individual anaerobic threshold and the fixed anaerobic threshold of 4 mmol.l^{-1} lactate. *International Journal of Sports Medicine* **3(2)**,105-110.

Toussaint, H.M. (2011) Biomechanics of drag and propulsion in front crawl swimming. In: *World Book of Swimming - From Science to Performance.* Eds: Seifert, L., Chollet, D. and Mujika, I.. New York: Nova Science Publishers. 3-20.

Vincent, J.W. (1999) *Statistics in Kinesiology*. 2nd edition. Human Kinetics, Champaign.

Wakayoshi, K., D'Acquisto, L.J., Cappaert, J.M. and Troup, J.P. (1995) Relationship between oxygen uptake, stroke rate and swimming velocity in competitive swimming. *International Journal of Sports Medicine* **16(1)**, 19-23.

Winter, D. (1990) *Biomechanics and motor control of human movement*. John Wiley and Sons, New York.

Zamparo, P., Bonifazi, M., Faina, M., Milan, A., Sardella, F. Schena, F. and Capelli, C. (2005) The energy cost of swimming in elite long distance swimmers. *European Journal of Applied Physiology* **94**, 697-704.

Zamparo, P., Capelli, C. and Pendergast, D.R., (2011) Energetics of swimming: a historical perspective. *European Journal of Applied Physiology* **111(5)**, 367-378.

Zamparo, P., Gatta, G., Pendergast, D. and Capelli, C. (2009) Active and passive drag: The role of trunk incline. *European Journal of Applied Physiology* **106(2)**, 195-205.

Zamparo, P., Pendergast, D. R., Mollendorf, J., Termin, A. and Minetti, A.E. (2005) An energy balance of front crawl. *European Journal of Applied Physiology* **94**, 134-144.

Key points

- In MLSS swimming intensity, stability of the stroke length and stroke frequency occurs after an initial adaptation.
- Efficiency indicators seem to be more sensitive to possible changes occurring through time at MLSS intensity.
- MLSS is a useful and practical swimming intensity to be maintained for a long period of time, but some constraints in technique can occur.

AUTHORS BIOGRAPHY

Pedro FIGUEIREDO

Employment

Member of the Centre of Research, Education, Innovation and Intervention in Sport of the Faculty of Sport of the University of Porto.

Degree

PhD

Research interests

Biomechanics and physiology applied to human locomotion.

E-mail: pedfig@me.com

Rafael NAZARIO

Employment

Collaborator of the Centre of Research, Education, Innovation and Intervention in Sport of the Faculty of Sport of the University of Porto.

Degree

MSc

Research interests

Biomechanics applied to swimming.

E-mail: rafaelnazario@gmail.com

Marisa SOUSA

Employment

Collaborator of the Centre of Research, Education, Innovation and Intervention in Sport of the Faculty of Sport of the University of Porto.

Degree

MSc

Research interests

Physiology applied to swimming, and Child Health.

E-mail: smarisacsousa@hotmail.com

Jailton Gregório PELARIGO

Employment

Sport Sciences PhD student. Collaborator of the Centre of Research, Education, Innovation and Intervention in Sport of the Faculty of Sport of the University of Porto.

Degree

MSc

Research interests

Physiology applied to swimming.

E-mail: jailtongp@hotmail.com

João Paulo VILAS-BOAS

Employment

Full Professor, Head of the Biomechanics Lab at the Porto University. Member of the Scientific Committee of Centre of Research, Education, Innovation and Intervention in Sport of the Faculty of Sport of the University of Porto.

Degree

PhD

Research interests

Biomechanics, exercise physiology applied to swimming.

E-mail: jpvb@fade.up.pt

Ricardo J. FERNANDES

Employment

Auxiliary Professor, Head of the Swimming Department at the Porto University. Member of Centre of Research, Education, Innovation and Intervention in Sport of the Faculty of Sport and of the Biomechanics Laboratory of the University of Porto.

Degree

PhD

Research interests

Swimming biophysical characterization specially centered on the availability and use of energy in swimming.

E-mail: ricfer@fade.up.pt

✉ **Ricardo Fernandes, Ph.D.**
Faculty of Sport, University of Porto,Head of the Swimming Department, Rua Dr. Plácido Costa, 91 4200-450 Porto Portugal