INTERNATIONAL JOURNAL OF SPORTS PHYSIOLOGY AND PERFORMANCE

Lactate threshold and swimming performance in world-class open water swimmers

Journal:	*International Journal of Sports Physiology and Performance*
Manuscript ID	IJSPP.2024-0342.R1 | DOI: 10.1123/ijspp.2024-0342
Manuscript Type:	Original Investigation
Date Submitted by the Author:	15-Oct-2024
Complete List of Authors:	López-Belmonte, Óscar; Universidad de Granada, Aquatics Lab. Department of Physical Education and Sports. Faculty of Sport Sciences Baldassarre, Roberto; University of Foro Italico, Rome, Department of Movement, Human and Health Sciences Ruiz-Navarro, Jesús J.; University of Granada, Aquatics Lab, Faculty of Sport Sciences, Department of Physical Education and Sports Bonifazi, Marco; Universita degli Studi di Siena, Department of Physiology Arellano, Raúl; University of Granada, Aquatics Lab, Department of Physical Education and Sports, Faculty of Sport Sciences; Raúl Arellano, Raúl Arellano Piacentini, Maria Francesca; University of Foro Italico, Rome, Department of Human Movement and Sport Sciences
Keywords:	anaerobic threshold, long-distance, endurance, aerobic capacity, physiology

Lactate threshold and swimming performance in world-class open water swimmers

Preferred running ahead: Lactate threshold in world-class swimmers

Submission type: Original investigation

López-Belmonte, Óscar[1]; Baldassarre, Roberto[2,3], Ruiz-Navarro, Jesús J.[1]; Bonifazi, Marco[4]; **Arellano, Raúl***[1]; Piacentini, Maria Francesca[5]

[1] Aquatics Lab. Department of Physical Education and Sports, Faculty of Sport Sciences, University of Granada, 18011, Granada, Spain

[2] Italian Swimming Federation, Rome, Italy

[3] Medicine and Sport Science Institute, Italian National Olympic Committee, Rome, Italy

[4] Department of Medical Biotechnology, University of Siena, 53100, Siena, Italy

[5] Department of Movement, Human and Health Sciences, University of Rome "Foro Italico", 00135, Rome, Italy

***Corresponding author:**
Raúl Arellano Colomina
Aquatics Lab. Department of Physical Education and Sports.
Faculty of Sport Sciences, Ctra. Alfacar S/N, 18011 Granada. Spain
University of Granada
email: r.arellano@ugr.es
Telf: +34662121881

Abstract word count: 249

Text-only word count: 3451

Number of tables: 4

Number of figures: 1

Lactate threshold and swimming performance in world-class open water swimmers

Submission type: Original investigation

Running head: Lactate threshold in world-class swimmers

Abstract word count: 249

Text-only word count: 3387

Number of tables: 4

Number of figures: 1

Abstract

Purpose: The assessment of the lactate threshold (LT) and its relationship to open water (OW) performance is crucial. This study aimed (1) to analyze the LT in world-class OW swimmers, to (2) compare swimming speed at LT (SS_{LT}) and swimming speed at 4 $mmol \cdot l^{-1}$ of blood lactate concentration ($[La^{-}]$) (SS_4), and (3) to examine the relationships between SS_{LT} and swimming performance. **Methods**: Twenty world-class and elite (11 males [26.4±3.0 y] and 9 females [25.8±3.6 y]) OW swimmers voluntarily participated. A total of 46 (29 male and 17 female tests) intermittent incremental tests (7x400-m) conducted in a 50-m pool were analyzed. Seasonal best performances on 400-, 800-, 1500-m and 10-km OW swimming events were obtained. **Results**: The SS_{LT} was 1.62 ± 0.02 (3.8±1.0 $mmol \cdot l^{-1}$) and 1.46 ± 0.04 $m \cdot s^{-1}$ (3.0±0.7 $mmol \cdot l^{-1}$) in males and females, respectively, which corresponded to 97% of the peak speed reached in the tests. There were no differences ($p = 0.148$) between SS_{LT} and SS_4 in males, however, SS_{LT} was lower ($p = 0.019$) than SS_4 in females. The SS_{LT} was negatively correlated with swimming performance, with the exception of 10-km OW and 400-m times in males and females, respectively. **Conclusions**: World-class and elite OW swimmers exhibited a great-developed aerobic capacity with LT close to their maximum speed. The SS_4 could be used as an approximation to SS_{LT} in males but overestimates true aerobic capacity in females. The LT is a useful tool for assessing performance, as OW swimmers with higher SS_{LT} showed better swimming performance.

Keywords: anaerobic threshold, long-distance, endurance, aerobic capacity, physiology.

INTRODUCTION

Open water (OW) swimming stands as one of the most challenging and breathtaking endurance disciplines in the swimming scene. The natural environments where OW swimming competitions are held (e.g., rivers or oceans), characterize these events with particular and changing conditions that swimmers must face.[1] Currently, the World Aquatics Championships program include the 5-km, 10-km distances and the mixed 4x1500-m relays, with the 10-km event only swum in the Olympic Games.[2] Since its inclusion in the 2008 Beijing Olympics, a substantial number of swimmers, particularly specialists in middle- and long-distance pool events, have also engaged in OW swimming races.[3,4] It is important to note that OW specialist swimmers incorporate 800-m to 5-km pool events into their competition schedule as part of their preparation for major events.[4–6] Thus, OW swimmers compete in the pool because they need to swim fast as the discipline evolves, indeed, previous research has shown that the fastest OW swimmers displayed higher speeds in middle- and long-distance pool swimming events.[4] Hence, this current trend among both disciplines may potentially modify the OW swimmers' profile to date.

Swimming testing is commonly integrated into elite training programs to accurately evaluate the competitive swimmers' performance.[7] Among a wide variety of parameters, the lactate threshold (LT) is recognized as a useful means of assessing a swimmer's aerobic capacity.[8] The LT is determined as the breakpoint of blood lactate concentration ([La⁻]) when arises from moderate to heavy intensities during intermittent incremental protocols.[8,9] In this regard, the LT assessment is essential in long-distance and OW swimmers, since most of the specialist training and competitions are performed at this intensity.[9,10] Moreover, the fixed [La⁻] at 4 $mmol·l^{-1}$ is considered the method traditionally used for assessing the aerobic capacity.[11] However, some controversial results have been shown about its relationship with LT, as some authors indicate an overestimation of the swimmers' aerobic capacity.[9] Therefore, due to the relevance of the LT determination for OW swimmers, testing the differences between swimming speed at LT (SS_{LT}) and the swimming speed corresponding to 4 $mmol·l^{-1}$ (SS_4) should provide valuable insights for coaches and scientists. On the other hand, an integrated physiological and biomechanical assessment of swimming performance provides a greater understanding of the performance,[12] as swimming changes in swimming technique may occur at speeds above the LT.[13] In this sense, stroke variables (e.g., stroke rate and length) play a crucial role as technical parameters in assessing how a swimmer's technique adapts to the increasing demands of exertion.[14,15] Hence, the SS_{LT} and its respective biomechanical assessment could be crucial for OW swimmers' performance.

The LT and its relationships with endurance performance is crucial.[16] The relationships between LT and endurance performance has been demonstrated to be crucial in sports like running and cycling.[16] However, there is a paucity of data regarding relationships in swimming, particularly among elite OW swimmers, with limited information available in both training and competition.[1] Thus, the LT determination and its association with swimming performance are essential to update the OW swimmers' profile. To the best of the authors' knowledge, only one study analyzed the LT in elite OW swimmers two decades ago.[17] However, this aforementioned study dates back to a time when OW swimming was not an Olympic discipline and therefore, given the rising participation in OW competitions, a different profile of OW swimmers may have emerged in recent years. In addition, the removal of the 25-km event from the 2023 World Championships program may have further impacted the evolving profile of OW swimmers. Thus, the aims of this study were (1) to analyze the LT through an incremental protocol test in world-class and elite OW swimmers, (2) to compare SS_{LT} and SS_4, and (3) to examine the relationships between SS_{LT} and swimming performance. Due to the current evolution of OW events, it is expected that elite OW swimmers achieve higher SS_{LT} compared to previous research.[17] Moreover, taking into account the results with long-distance swimmers,[9] the SS_4 would be higher than the SS_{LT}, overestimating the aerobic capacity. Finally, swimmers with higher SS_{LT} would exhibit better performance, as it is key in long-distance swimming.

METHODS

Participants

Twenty world-class and elite[18] OW swimmers (Table 1), members of national swimming teams and training together under the direction of the same coach, voluntarily participated in the current study. According to the classification of Ruiz-Navarro et al.[17], participants were classified between performance Level 1 (≥ 875 World Aquatics Points) and 3 (650-

799 World Aquatics Points). During the 2022 and 2023 seasons, the OW swimmers performed three 7x400-m intermittent incremental protocol tests (October 2022, February and October 2023), with an average weekly training of 54.0 ± 16.7 km during these seasons. From the total sample, fifteen swimmers (9 males and 6 females) performed the test more than once, thus a total of 46 incremental tests were analyzed (29 male and 17 female tests). The study was conducted according to the code of ethics of the World Medical Association (Declaration of Helsinki) and was approved by the University Ethics Committee (*project code: removed to keep anonymity*).

Please insert Table 1

Data collection

The protocol conducted was replicated during the three occasions. All tests took place in a 50-m long-course pool with a water temperature of ~26ºC. During the 3 to 5 days prior to each test, training volume was reduced by approximately 30-40% to suit the individual characteristics of each swimmer. All tests were conducted following a standardized training week for all participants to ensure consistency across the three occasions. The swimmers performed a 1200-m standardized warm-up from low to moderate intensity prior to the swimming assessment. The 7x400-m intermittent incremental protocol consisted of seven steps, from easy to maximal effort, with 30-s rest intervals. All tests were conducted with in-water starts and at the same time of the day to avoid circadian variations.[20] Swimming speed of the first 400-m step was set at 80% of the 400-m freestyle seasonal best and subsequently increased by 3% per step. The 400-m times performed (s) were measured through a stopwatch (FINIS 3X-300M, FINIS, Inc., USA) by an expert swimming researcher. The final times obtained were converted in swimming speed for each 400-m step ($m \cdot s^{-1}$). The [La^-] were analyzed with a portable lactate analyzer (Lactate Pro 2.0, Arkray Inc., Tokyo, Japan) from the swimmers' right lobe right after each 400-m step and at the end of the test immediately after the last step, at 1, and every 2 min until the peak ([La^-]$_{peak}$) was reached. The self-reported Rating of Perceived Exertion (RPE)[21] was obtained from the swimmers immediately after each step. Stroke rate (SR) was obtained by considering three upper limb cycles divided by the time elapsed during this action and multiplied by 60 to consider the number of cycles per minute.

Stroke length (SL) was calculated from the ratio between swimming speed, and SR and stroke index (SI) was computed as the product of swimming speed and SL.[22] Each stroke variable was measured every 50-m and the mean of the eight laps was computed.

Methodology

The LT was determined by projecting the x-axis intersection of the lines connecting the two highest and two lowest points of the speed lactate curve[8,23] (Figure 1). From this intersection, $[La^{-}]$ corresponding to individual LT ($[La^{-}]_{LT}$) and swimming speed at LT (SS_{LT}) were obtained (mean $R^2 = 0.98$; range R^2: 0.89-0.99; mean r = 0.98; range r = 0.94-0.99). Swimming speed corresponding to $[La^{-}]$ at 4 $mmol \cdot l^{-1}$ (SS_4) was interpolated[11] (Figure 1). Heart rate (HR) was registered immediately after each 400-m step and the maximum value (HR_{max}) was obtained after the last step using the Polar H10 HR sensor (Polar Electro OY, Kempele, Finland). Moreover, SR, SL, SI, HR and RPE at individual anaerobic threshold (SR_{LT}, SL_{LT}, SI_{LT}, HR_{LT} and RPE_{LT}) were determined by linear interpolation between the values of each variable from the steps immediately below and above $[La^{-}]_{LT}$.

The best seasonal performance in each event and World Aquatics Points[2] in official 2023 long-course competitions on 400-, 800- and 1500-m events were retrieved per swimmer from the public access website www.swimrankings.net (Table 3). In addition, the times performed in 10-km OW swimming events were obtained from the official websites of the European[21] and World Aquatics.[2] Due to the changing OW conditions,[1] the best and worst race times were removed and the mean of two 10-km OW events per swimmer were obtained. All times were collected from international and national events held between October 2022 and October 2023.

Please insert Figure 1

Statistical analysis

Descriptive statistics (mean and standard deviation [SD]) for the swimming performance, physiological and biomechanical variables were obtained. Normal distribution of the data was checked with the Shapiro-Wilk test. A paired sample t-test was conducted to verify differences between SS_{LT} and SS_4. Mean values of each swimmer were considered to calculate the differences between these variables. Pearson's correlations were used to determine the association between SS_{LT} and seasonal best performances. The threshold correlation values were defined as: ≤ 0.1 trivial; < 0.1-0.3 small; > 0.3-0.5 moderate; > 0.5-0.7 large; > 0.7-0.9 very large; and > 0.9-1.0 almost perfect.[25] All statistical analyses were conducted separately by sex. The significance level was set up at $p < 0.05$ and all the statistical analyses were performed using the Statistical Package for the Social Sciences (SPSS 28.0, IBM Corporation Chicago, IL, USA).

Results

The mean and SD derived from the intermittent incremental protocol tests are presented in Table 2. Seasonal best performances obtained, swimming speed, physiological and biomechanical variables derived from the tests are shown in Table 3. In males, the SS_{LT} ranged from 1.58 to 1.63 $m \cdot s^{-1}$ and $[La^{-}]_{LT}$ from 2.7 to 6.0 $mmol \cdot l^{-1}$. In females, the SS_{LT} presented a range from 1.42 to 1.47 $m \cdot s^{-1}$ and $[La^{-}]_{LT}$ from 2.0 to 4.1 $mmol \cdot l^{-1}$. The SS_{LT} corresponded to 97% of the peak swimming speed achieved in the incremental protocol in both sexes. Similar HR_{LT} percentages of 96 and 97% were reached with respect to HR_{max} in males and females, respectively. No difference ($p = 0.148$) was observed between SS_{LT} and SS_4 in males, while a significant difference ($p = 0.019$) was found in females. Pearson correlation coefficients between SS_{LT} and swimming performance are shown in Table 4. In males, the SS_{LT} presented large to very large negative correlations with pool swimming performance. In females, the SS_{LT} presented large negative correlations with pool and OW swimming performance, with no significant association with 400-m time (Table 4).

Please insert Table 2

Please insert Table 3

Please insert Table 4

DISCUSSION

The current study aimed to analyze the LT in world class and elite OW swimmers, compare SS_{LT} and SS_4, and examine the relationships between SS_{LT} and swimming performance. The main findings of this study indicated high SS_{LT} values in both male and female OW swimmers close to their maximum values derived from the incremental tests. While no differences between SS_{LT} and SS_4 were observed in males, females exhibited lower SS_{LT} than SS_4. On the other hand, due to the negative association between SS_{LT} and swimming performance times, the findings suggest that SS_{LT} is a reliable indicator of performance in elite OW swimmers.

Despite LT assessment is crucial for long-distance and OW swimmers,[1,9] few studies have explored the LT or SS_{LT} in elite OW swimmers.[17] As it was expected, the SS_{LT} reported in this study (Table 3) were considerably higher than those reported by previous research, which indicated 1.34-1.32 $m \cdot s^{-1}$ for elite male and female OW swimmers.[17] The paradigm shift in OW events with its inclusion in the Olympic Games program and the emergence of pool swimmers[3,4] has led to a different OW swimmer profile, with swimmers able to reach higher speeds at LT. In fact, the SS_{LT} represented the 97% of the peak swimming speed reached in the tests, considerably higher than the 89-94% previously reported in 2004.[17] This near-peak swimming speed reach at LT reflects the superbly developed aerobic capacity of these swimmers, which allows them to swim fast during prolonged period of times. Hence, given that successful OW swimmers must maintain swimming speeds at or above the LT,[10] these values may be used as important indicators for researchers and contribute to updating the OW swimmers' profiles.

In the case of $[La^-]_{LT}$, OW swimmers exhibited similar values (Table 3) to those reported in elite pool swimmers (3.2-3.6 $mmol \cdot l^{-1}$),[8] whereas long-distance swimmers exhibited lower $[La^-]_{LT}$ (1.8-2.2 $mmol \cdot l^{-1}$),[9] away from the fixed 4 $mmol \cdot l^{-1}$ traditionally considered as the LT.[11] However, swimmers' performance level of the mentioned study was notably lower than the presented here, as the mean SS_{LT} and SS_4 were 1.07 and 1.18 $m \cdot s^{-1}$, respectively. In this regard, several studies have indicated that SS_4 value does not represent the individualized SS_{LT},[9,26] overestimating the actual swimmers' aerobic capacity.[9] In this regard, in the current study, no differences (p = 0.148) were found between SS_{LT} and SS_4 in males (Table 3), likely induced by the high variability obtained in $[La^-]_{LT}$ (SD: 1.0 mmol·l^{-1}; range from 2.7 to 6.0 mmol·l^{-1}). Hence, while some swimmers LT was below the traditional fixed 4 mmol·l^{-1} others were above. Indeed, due to the large individual variability of these values at LT, some authors have determined the LT training zone between 2 and 4 mmol·l^{-1}.[27,28] Hence, considering the lack of difference between SS_{LT} and SS_4, the SS_4 could be used as an approximation to LT in elite OW male swimmers, however, it is of paramount importance to address data variability and consider individual differences when attempting to generalize findings to the entire sample. On the other hand, elite OW female swimmers presented $[La^-]_{LT}$ notably below the 4 mmol·l^{-1} (3.0 mmol·l^{-1}), with significantly higher SS_4 than SS_{LT}, which is consistent with previous findings.[9,13] In that sense, it is important to consider the influence of sex on $[La^-]$ parameters, as females have a less developed anaerobic metabolism,[29] larger Type I fiber proportion[30] and/or a more efficient technique due to the characteristics of the females' body composition.[31] This enables them to achieve a higher percentage of their personal best with lower $[La^-]$ than males.[32] Therefore, swimmers and coaches should determine the individual swimmers' LT in females, since SS_4 may denote performing considerably beyond the SS_{LT}.

Regarding the $[La^-]_{Peak}$ reached by males (8.7 mmol·l^{-1}), similar values were obtained by an OW World Champion (8.5 mmol·l^{-1})[27] and slightly higher than in elite OW swimmers (7.4 mmol·l^{-1}) after incremental protocols.[17] In females, the $[La^-]_{Peak}$ obtained was also similar (6.9 mmol·l^{-1}) that those reported in elite OW female swimmers (7.6 mmol·l^{-1}).[17] In this context, although $[La^-]$ is a useful indicator of swimmers' individual performance,[8,33] a higher swimming speed at a given $[La^-]$ does not necessarily mean a better aerobic capacity, as this may indicate both a reduced anaerobic capacity or an improved aerobic capacity.[34] Therefore, despite the $[La^-]$ assessment is essential to determine LT in OW swimmers, it is important to support these values with other physiological variables. In this sense, the HR_{LT} and HR_{max} obtained (Table 3) contrasted with the lower values previously reported, especially in the HR_{LT}.[17,27] However, when comparing percentage instead of absolute values, the HR_{LT} represented 93% of the HR_{max}, similar to those obtained in this study (96-97%). Therefore, these percentages at LT (SS_{LT} or HR_{LT}) with regards to maximal values underscore the remarkable development of aerobic capacity in elite OW swimmers.

As part of the intricate array of variables that determine performance,[35] the swimming technique should be enhanced through the range of training and competition speeds[13]. Thus, biomechanical assessment and its association with LT is crucial for OW swimmers. Previous studies have reported an inverse relationship between SR and SL, leading towards increases in SR and decreases in SL to reach higher swimming speed throughout the tests,[13,15] which was also observed in this study (Table 2). Moreover, these stoke variables at LT are considered an easy and non-invasive tool to provide useful information for training and swimmers' monitoring.[14] In this sense, the SR_{LT} reported in previous research[17] was lower in males (33.9 ± 1.4 cycles·min^{-1}) and higher in females (44.9 ± 1.6 cycles·min^{-1}) compared to those SR_{LT} values obtained in this study (Table 3). In the case of SL, swimmers should try to maintain SL as speed increases,[14] which means that higher SL_{LT} and SI_{LT} values would be advantageous for a better performance. This fact was confirmed by the higher SL_{LT} obtained (Table 3) compared to the 1.7-2.2 m exhibited by well-trained swimmers.[9,14] However, when comparing stroke variables between swimmers, it is important to note that each swimmer must adopt an optimal balance between SR and SL to achieve higher speeds with lower energy cost.[12] Thus, the analysis of these variables corresponding to LT intensities may be relevant for controlling or assessing individual swimming technique, which could provide practical information in the training context.

Swimming performance and its associations with LT is scarce in elite OW swimmers.[1] In line with other endurance sports,[16] the results of the correlations showed that the higher the SS_{LT}, the better the performance in pool and OW events (Table 4). However, this was not the case between SS_{LT} and 10-km OW times in males. Despite OW swimmers swim close or at LT, the effect of the currents or the speed variations during the race, as well as changes between groups,[1,36] may affect to the 10-km OW times obtained in males, which could explain the lack of association between SS_{LT} and OW performance. Indeed, the OW swimming speed was 0.09 $m\cdot s^{-1}$ lower than SS_{LT}. On the other hand, the absence of association between SS_{LT} and 400-m performance in females may be explained by the higher variability between swimmers when compared to the other distances performance (Table 3). Moreover, despite aerobic capacity also plays an important role in 400-m swimming, the aerobic power could be more decisive in this distance,[37] as the duration differs significantly between a 400-m (~ 4 min) and a 10-km OW event (~ 2 h). Therefore, despite some exceptions, the relationships between SS_{LT} and most of the seasonal best performances suggest that LT may be a useful performance indicator in elite OW swimmers.

It is important to highlight the high performance level of the OW swimmers comprised in the current study, some of them gold medalists at Olympic Games and World Championships. Moreover, the participants were under the instructions of the same swimming coach, allowing a better training control of the sample. In addition, the sex-differentiated analysis conducted in this study provides relevant information for both male and female swimmers. A limitation of this study is that the reductions in training volume prior to each test were not exactly the same, which may have introduced variability between assessments. In addition, each swimmer's seasonal best performances, collected at different points during the 2023 season, may have influenced the correlations with SS_{LT}. On the other hand, although the interpolation method for determining LT is accurate for competitive swimmers, it is important to note that other methods may lead to different results.[38] Finally, it should be noted that performance differs between pool and OW swimming conditions, which may lead different physiological and biomechanical demands in the changing natural environment,[39,40] Thus, future research should consider the analysis in an OW environment to facilitate a more comprehensive physiological examination within the competitive context.

PRACTICAL APPLICATIONS

From a practical point of view, the results obtained provide new insights for swimmers and coaches, as LT assessment is essential to diagnosis the aerobic capacity and swimming performance. In order to succeed, swimmers should exhibit higher values at LT, obtaining SS_{LT} or HR_{LT} close to the maximums achieved in incremental tests. Considering the high performance level, these results provide valuable benchmarks for scientists and coaches, and maybe applicable to other endurance sports where LT is key to performance.

CONCLUSIONS

Elite OW swimmers' profile exhibited a remarkable development of aerobic capacity, obtaining higher SS_{LT} compared to previous research. These findings were supported by the SS_{LT} or HR_{LT} corresponded to 96-97% of the maximum values achieved in the incremental tests, which indicates that swimmers are capable of maintaining near-maximum intensity for extended periods. The SS_4 may be used as an approximation to SS_{LT} in males, although caution should be taken due to the likely variability between swimmers. On the other hand, SS_{LT} was lower than SS_4 in females, overestimating the aerobic capacity when SS_4 is used to establish the LT. Finally, the LT is a useful tool for assessing performance, as elite OW swimmers with higher SS_{LT} showed better performance in most swimming events.

ACKNOWLEDGMENTS

Removed to keep anonymity

This study was supported PID2022-142147NB-I00. SWIM III: Effect of the application 392 of different specific warm-ups [PAPE: Postactivation Performance Enhancement] on 393 muscular, physiological and technical response in competitive swimmers. Funded by 394 MCIN/AEI/10.13039/501100011033 and, as appropriate, by "ERDF A way of making 395 Europe", by the "European Union NextGenerationEU/PRTR". This article is a part of an 396 international thesis belonging to the PhD Program of Biomedicine (B11.56.1) from the 397 University of Granada supported by the Ministry of Universities: FPU19/02477 grant.

REFERENCES

1. Baldassarre R, Bonifazi M, Zamparo P, Piacentini MF. Characteristics and challenges of open-water swimming performance: A review. *Int J Sports Physiol Perform*. 2017;12(10):1275-1284. doi:10.1123/ijspp.2017-0230

2. World Aquatics. World Aquatics Points, united by water 2024. Published 2024. Accessed May 1, 2024. https://www.worldaquatics.com/SWIMMING/POINTS

3. Shaw G, Koivisto A, Gerrard D, Burke LM. Nutrition considerations for open-water swimming. In: *International Journal of Sport Nutrition and Exercise Metabolism*. Vol 24. ; 2014:373-381. doi:10.1123/ijsnem.2014-0018

4. Baldassarre R, Pennacchi M, La Torre A, Bonifazi M, Piacentini MF. Do the fastest open-water swimmers have a higher speed in middle- and long-distance pool swimming events? *J Funct Morphol Kinesiol*. 2019;4(1):1-15. doi:10.3390/jfmk4010015

5. López-Belmonte Ó, Ruiz-Navarro JJ, Gay A, Cuenca-Fernández F, Mujika I, Arellano R. Analysis of pacing and kinematics in 3000 m freestyle in elite level swimmers. *Sport Biomech*. Published online 2023:1-17. doi:10.1080/14763141.2023.2184418

6. Baldassarre R, Ieno C, Bonifazi M, Piacentini MF. Pacing and hazard score of elite open water swimmers during a 5-km indoor pool race. *Int J Sports Physiol Perform*. 2021;16(6):796-801. doi:10.1123/ijspp.2020-0197

7. Anderson M, Hopkins W, Roberts A, Pyne D. Ability of test measures to predict competitive performance in elite swimmers. *J Sports Sci*. 2008;26(2):123-130. doi:10.1080/02640410701348669

8. Pyne DB, Lee H, Swanwick KM. Monitoring the lactate threshold in world-ranked swimmers. *Med Sci Sports Exerc*. 2001;33(2):291-297. doi:10.1097/00005768-200102000-00019

9. Fernandes RJ, Sousa M, MacHado L, Vilas-Boas JP. Step length and individual anaerobic threshold assessment in swimming. *Int J Sports Med*. 2011;32(12):940-946. doi:10.1055/s-0031-1283189

10. Rodriguez L, Veiga S. Effect of the pacing strategies on the open-water 10-km

world swimming championships performances. *Int J Sports Physiol Perform*. 2018;13(6):694-700. doi:10.1123/ijspp.2017-0274

11. Mader A, Heck H, Hollman W. Evaluation of lactic acid anaerobic energy contribution by determination of post exercise lactic acid concentration of ear capillary blood in middle-distance runners and swimmers. *Exerc Physiol*. 1978;4:187-200.

12. Barbosa TM, Bragada JA, Reis VM, Marinho DA, Carvalho C, Silva AJ. Energetics and biomechanics as determining factors of swimming performance: Updating the state of the art. *J Sci Med Sport*. 2010;13(2):262-269. doi:10.1016/j.jsams.2009.01.003

13. Figueiredo P, Morais P, Vilas-Boas JP, Fernandes RJ. Changes in arm coordination and stroke parameters on transition through the lactate threshold. *Eur J Appl Physiol*. 2013;113(8):1957-1964. doi:10.1007/s00421-013-2617-8

14. Oliveira MFM, Caputo F, Lucas RD, Denadai BS, Greco CC. Physiological and stroke parameters to assess aerobic capacity in swimming. *Int J Sports Physiol Perform*. 2012;7(3):218-223. doi:10.1123/ijspp.7.3.218

15. Psycharakis SG, Cooke CB, Paradisis GP, O'Hara J, Phillips G. Analysis of selected kinematic and physiological performance determinants during incremental testing in elite swimmers. *J Strength Cond Res*. 2008;22(3):951-957. doi:10.1519/JSC.0b013e31816a6364

16. Faude O, Kindermann W, Meyer T. Lactate Threshold Concepts. *Sport Med*. 2009;39(6):469-490. doi:10.2165/00007256-200939060-00003

17. VanHeest JL, Mahoney CE, Herr L. Characteristics of elite open-water swimmers. *J Strength Cond Res*. 2004;18(2):302-305. doi:10.1519/R-13513.1

18. McKay AKA, Stellingwerff T, Smith ES, et al. Defining Training and Performance Caliber: A Participant Classification Framework. *Int J Sports Physiol Perform*. 2022;17(2):317-331. doi:10.1123/ijspp.2021-0451

19. Ruiz-Navarro JJ, López-Belmonte Ó, Gay A, Cuenca-Fernández F, Arellano R. A new model of performance classification to standardize the research results in swimming. *Eur J Sport Sci*. 2023;23(4). doi:10.1080/17461391.2022.2046174

20. Atkinson G, Reilly T. Circadian variation in sports performance. *Sport Med*. 1996;21(4):292-312. doi:10.2165/00007256-199621040-00005

21. Borg GAV. Psychophysical bases of perceived exertion. *Med Sci Sports Exerc*. 1982;14(5):377-381. Accessed December 21, 2023. https://europepmc.org/article/med/7154893

22. Costill DL, Kovaleski J, Porter D, Kirwan J, Fielding R, King D. Energy expenditure during front crawl swimming: Predicting success in middle-distance events. *Int J Sports Med*. 1985;6(5):266-270. doi:10.1055/s-2008-1025849

23. Toubekis AG, Tsami AP, Tokmakidis SP. Critical velocity and lactate threshold in young swimmers. *Int J Sports Med*. 2006;27(2):117-123. doi:10.1055/s-2005-837487

24. European Aquatics. Europen Aquatics. Published 2024. Accessed May 1, 2024. https://www.len.eu/

25. Hopkins WG, Marshall SW, Batterham AM, Hanin J. Progressive statistics for studies in sports medicine and exercise science. *Med Sci Sports Exerc*. 2009;41(1):3-12. doi:10.1249/MSS.0b013e31818cb278

26. Fernandes RJ, Vilas-Boas JP. Time to exhaustion at the VO2max velocity in swimming: A review. *J Hum Kinet*. 2012;32(1):121-134. doi:10.2478/v10078-012-0029-1

27. Pla R, Aubry A, Resseguier N, Merino M, Toussaint JF, Hellard P. Training Organization, Physiological Profile and Heart Rate Variability Changes in an Open-water World Champion. *Int J Sports Med*. 2019;40(8):519-527. doi:10.1055/a-0877-6981

28. Hellard P, Avalos-Fernandes M, Lefort G, et al. Elite swimmers' training patterns in the 25 weeks prior to their season's best performances: Insights into periodization from a 20-years cohort. *Front Physiol*. 2019;10(APR). doi:10.3389/fphys.2019.00363

29. Stanula A, Maszczyk A, Roczniok R, et al. The development and prediction of athletic performance in freestyle swimming. *J Hum Kinet*. 2012;32(1):97-107. doi:10.2478/v10078-012-0027-3

30. Staron RS, Hagerman FC, Hikida RS, et al. Fiber type composition of the vastus lateralis muscle of young men and women. *J Histochem Cytochem*. 2000;48(5):623-629. doi:10.1177/002215540004800506

31. Barbosa TM, Fernandes RJ, Keskinen KL, Vilas-Boas JP. The influence of stroke mechanics into energy cost of elite swimmers. *Eur J Appl Physiol*. 2008;103(2):139-149. doi:10.1007/s00421-008-0676-z

32. Holfelder B, Brown N, Bubeck D. The Influence of Sex, Stroke and Distance on the Lactate Characteristics in High Performance Swimming. *PLoS One*. 2013;8(10). doi:10.1371/journal.pone.0077185

33. Bonifazi M, Martelli G, Marugo L, Sardella F, Carli G. Blood lactate accumulation in top level swimmers following competition. *J Sports Med Phys Fitness*. 1993;33(1):13-18. Accessed May 15, 2024. https://europepmc.org/article/med/8350602

34. Olbrecht J. Lactate production and metabolism in swimming. In: *World Book of Swimming: From Science to Performance*. ; 2011:255-275. Accessed May 15, 2024. https://www.researchgate.net/profile/Jan-Olbrecht/publication/286580355_Lactate_production_and_metabolism_in_swimming/links/56a1fde308ae984c449af74a/Lactate-production-and-metabolism-in-swimming.pdf

35. Barbosa TM, Costa MJ, Marinho DA. Proposal of a deterministic model to explain swimming performance. *Int J Swim Kinet*. 2013;2(1):1-54. Accessed July 8, 2024. https://bdigital.ipg.pt/dspace/handle/10314/3184

36. Baldassarre R, Bonifazi M, Piacentini MF. Pacing profile in the main international open-water swimming competitions. *Eur J Sport Sci*. 2019;19(4):422-431. doi:10.1080/17461391.2018.1527946

37. Rodríguez FA, Mader A. Energy systems in swimming. In: *World Book of Swimming: From Science to Performance*. ; 2011:225-240. doi:10.13140/2.1.3260.5128

38. Arsoniadis GG, Nikitakis IS, Peyrebrune M, Botonis PG, Toubekis AG. The Method but Not the Protocol Affects Lactate-Threshold Determination in Competitive Swimmers. *Int J Sports Physiol Perform*. Published online 2024:1-

10. doi:10.1123/ijspp.2023-0389

39. Zacca R, Neves V, da Silva Oliveira T, et al. 5 Km Front Crawl in Pool and Open Water Swimming: Breath-By-Breath Energy Expenditure and Kinematic Analysis. *Eur J Appl Physiol*. 2020;120(9):2005-2018. doi:10.1007/s00421-020-04420-7

40. López-Belmonte Ó, Gay A, Ruiz-Navarro JJ, Cuenca-Fernández F, Cejuela R, Arellano R. Open Water Swimming in Elite Triathletes: Physiological and Biomechanical Determinants. *Int J Sports Med*. 2024;45:1-10. doi:10.1055/a-2289-0873

TABLE AND FIGURE CAPTIONS

Table 1. Mean ± standard deviation of the physical characteristics and performance variables of elite open water swimmers (n = 20).

Table 2: Mean ± standard deviation of the performance, physiological and biomechanical variables obtained in the 7x400-m intermittent incremental protocol tests in elite open water swimmers.

Table 3: Mean ± standard deviation of the seasonal best performances obtained, swimming speed, physiological and biomechanical variables derived from the intermittent incremental protocol tests in elite open water swimmers.

Table 4: Pearson correlation coefficients between swimming speed and seasonal best performances. Black (e.g., 0.999) and grey (e.g., 0.999) font colour for male (n = 11) and female (n = 9) elite open water swimmers, respectively.

Figure 1. Example of blood lactate concentration $[La^-]$ to speed swimming curve obtained in the 7x400-m intermittent incremental protocol test of an Olympic gold medalist swimmer. The arrows indicate the lactate threshold (LT) and speed corresponding to a $[La^-]$ of 4 $mmol \cdot l^{-1}$ (SS_4). Heart rate (HR) trend line is represented during the test.

Table 1: Mean ± standard deviation of the physical characteristics of elite open water swimmers (n = 20).

	Males (n = 11)	**Females** (n = 9)
Age (years)	26.4 ± 3.0	25.8 ± 3.6
Height (cm)	185.7 ± 3.8	173.3 ± 5.3
Body mass (kg)	74.7 ± 5.8	64.4 ± 3.9
Body mass index ($kg \cdot m^{-2}$)	21.7 ± 1.8	21.1 ± 1.3

Table 2: Mean ± standard deviation of the performance, physiological and biomechanical variables obtained in the 7x400-m intermittent incremental protocol tests in elite open water swimmers.

	Performance			Physiological variables			Biomechanical variables		
	Step number	400-m time (s)	Swimming speed (m·s^{-1})	Blood lactate concentration (mmol·L^{-1})	Heart rate (beats·min^{-1})	Rate of perceived exertion	Stroke rate (cycles·min^{-1})	Stroke length (m)	Stroke index (m^2·s^{-1})
Male's tests (n = 29)	1	286.8 ± 6.9	1.40 ± 0.03	1.5 ± 0.2	137 ± 8	1.0 ± 0.3	28.59 ± 2.74	2.79 ± 0.37	3.89 ± 0.48
	2	275.8 ± 6.9	1.45 ± 0.04	1.5 ± 0.2	149 ± 11	1.7 ± 0.5	30.78 ± 3.07	2.78 ± 0.21	4.03 ± 0.25
	3	267.6 ± 5.1	1.50 ± 0.03	1.6 ± 0.2	156 ± 9	2.5 ± 0.8	32.31 ± 2.96	2.73 ± 0.20	4.08 ± 0.25
	4	259.8 ± 4.3	1.54 ± 0.02	2.1 ± 0.4	164 ± 9	3.5 ± 0.8	34.65 ± 2.89	2.62 ± 0.20	4.03 ± 0.30
	5	252.1 ± 3.1	1.59 ± 0.02	2.9 ± 0.7	173 ± 7	4.9 ± 0.9	36.50 ± 3.11	2.56 ± 0.20	4.06 ± 0.30
	6	246.3 ± 3.0	1.63 ± 0.02	4.5 ± 1.5	179 ± 7	6.7 ± 1.1	38.26 ± 2.88	2.50 ± 0.18	4.06 ± 0.28
	7	239.4 ± 2.8	1.67 ± 0.02	8.7 ± 2.5	184 ± 5	9.5 ± 0.7	41.17 ± 3.19	2.39 ± 0.19	3.99 ± 0.32
Female's tests (n = 17)	1	308.2 ± 8.8	1.30 ± 0.04	1.6 ± 0.4	142 ± 8	0.8 ± 0.4	32.51 ± 2.24	2.35 ± 0.18	3.05 ± 0.29
	2	297.3 ± 6.2	1.35 ± 0.03	1.5 ± 0.4	150 ± 9	1.5 ± 0.6	34.57 ± 2.48	2.29 ± 0.17	3.08 ± 0.25
	3	290.1 ± 5.1	1.38 ± 0.03	1.7 ± 0.5	161 ± 6	2.5 ± 1.2	36.16 ± 2.29	2.24 ± 0.15	3.09 ± 0.23
	4	283.5 ± 3.9	1.41 ± 0.02	2.0 ± 0.6	169 ± 6	3.5 ± 1.5	37.53 ± 2.59	2.21 ± 0.15	3.12 ± 0.22
	5	276.8 ± 5.3	1.45 ± 0.03	2.6 ± 1.0	176 ± 7	4.7 ± 1.9	38.92 ± 2.63	2.18 ± 0.14	3.15 ± 0.18
	6	272.6 ± 4.8	1.47 ± 0.03	3.1 ± 1.0	180 ± 9	5.3 ± 2.2	39.95 ± 2.92	2.16 ± 0.14	3.17 ± 0.18
	7	266.6 ± 6.3	1.50 ± 0.03	6.9 ± 1.8	184 ± 11	8.5 ± 1.9	41.74 ± 3.44	2.12 ± 0.15	3.17 ± 0.19

Table 3: Mean ± standard deviation of the seasonal best performances obtained, swimming speed, physiological and biomechanical variables derived from the intermittent incremental protocol tests in elite open water swimmers.

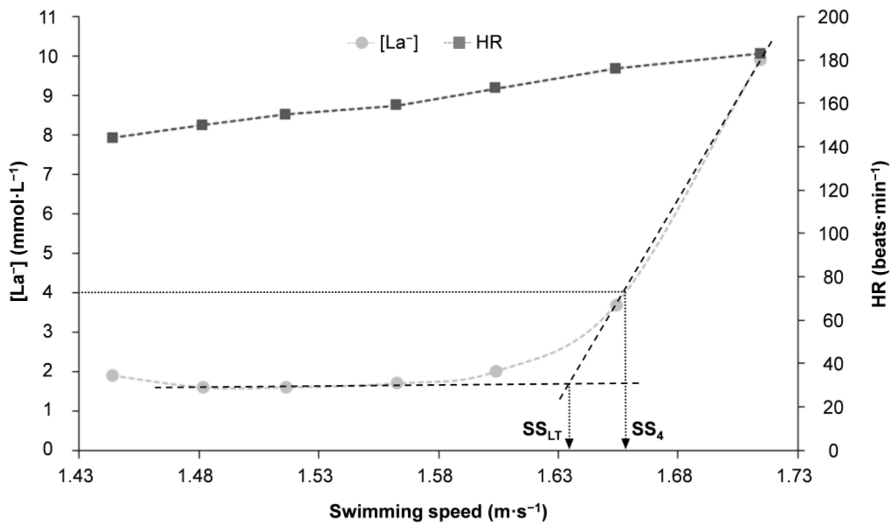
	Males (n = 11)	Females (n = 9)
Swimming performance		
400-m time (s)	232.4 ± 4.6	260.1 ± 7.4
400-m World Aquatics Points	851 ± 48	753 ± 65
800-m time (s)	477.5 ± 8.0	526.4 ± 13.2
800-m World Aquatics Points	850 ± 42	783 ± 59
1500-m time (s)	911.7 ± 18.9	1001.4 ± 24.9
1500-m World Aquatics Points	874 ± 54	779 ± 58
Best 10-km open water time (s)	6556.0 ± 105.9	7289.4 ± 112.6
Swimming speed		
SS_{LT} ($m \cdot s^{-1}$)	1.62 ± 0.02	1.46 ± 0.04
SS_4 ($m \cdot s^{-1}$)	1.62 ± 0.03	1.48 ± 0.03
Physiological variables		
$[La^-]_{LT}$ ($mmol \cdot l^{-1}$)	3.8 ± 1.0	3.0 ± 0.7
$[La^-]_{Peak}$ ($mmol \cdot l^{-1}$)	8.7 ± 2.5	6.9 ± 1.8
HR_{LT} ($beats \cdot min^{-1}$)	177 ± 6	178 ± 9
HR_{max} ($beats \cdot min^{-1}$)	184 ± 5	184 ± 11
RPE_{LT}	5.8 ± 0.9	5.5 ± 1.6
Biomechanical variables		
SR_{LT} ($cycles \cdot min^{-1}$)	38.05 ± 2.85	39.54 ± 3.33
SL_{LT} (m)	2.57 ± 0.18	2.20 ± 0.14
SI_{LT} ($m^2 \cdot s^{-1}$)	4.17 ± 0.30	3.23 ± 0.18

SS_{LT}: swimming speed corresponding to lactate threshold; SS_4: swimming speed corresponding to $[La^-]$ of 4 $mmol \cdot l^{-1}$; $[La^-]_{LT}$: blood lactate concentration corresponding to lactate threshold; $[La^-]_{Peak}$: peak blood lactate concentration; HR_{LT}: heart rate corresponding to anaerobic threshold; HR_{max}: maximum heart rate; RPE_{LT}: rate of perceived exertion at lactate threshold; SR_{LT}, SL_{LT} and SI_{LT}: stroke rate, length and index corresponding to anaerobic threshold.

Table 4: Pearson correlation coefficients between swimming speed and seasonal best performances. Black (e.g., 0.999) and grey (e.g., 0.999) font colour for male (n = 11) and female (n = 9) elite open water swimmers, respectively.

Variables	1.	2.	3.	4.	5.
1. SS_{LT} ($m \cdot s^{-1}$)		- 0.628*	- 0.825**	-0.710**	- 0.378
2. Best 400-m time (s)	- 0.570		0.726**	0.352	- 0.140
3. Best 800-m time (s)	- 0.629*	0.942**		0.785**	0.139
4. Best 1500-m time (s)	- 0.681*	0.842**	0.919**		0.280
5. Mean 10-km open water times (s)	- 0.694*	0.374	0.180	0.244	

SS_{LT}: swimming speed corresponding to lactate threshold. *$p < 0.05$; **$p < 0.01$



Example of blood lactate concentration ([La−]) to speed swimming curve obtained in the 7x400-m intermittent incremental protocol test of an Olympic gold medalist swimmer. The arrows indicate the lactate threshold (LT) and speed corresponding to a [La−] of 4 mmol·1−1 (SS4). Heart rate (HR) trend line is represented during the test.

1411x793mm (144 x 144 DPI)