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Open water swimming in elite triathletes: physiological and biomechanical determinants

ABSTRACT

This study aimed (i) to analyse the 1500-m open water swimming performance, (ii) to examine the associations between physiological and biomechanical variables with swimming performance and (iii) to determine which variables can predict swimming performance in triathletes. Fourteen elite triathletes (23.4 ± 3.8 y) performed a 1500-m in open water swimming conditions. Swimming performance was considered as World Aquatics Points obtained in the 1500-m open water swimming test. Heart rate, end-exercise oxygen uptake (EE$\dot{V}O_2$) and blood lactate concentrations were assessed. The initial 250-m of the 1500-m swimming test presented the highest values of biomechanical variables [i.e., swimming speed, stroke rate (SR), length (SL), index (SI)] in males. A decrease in SL was observed in the last 250-m in both sexes. Positive association were found between EE$\dot{V}O_2$ (r=0.513; p=0.030), swimming speed (r=0.873; p<0.001) and SI (r=0.704; p=0.002) with swimming performance. In contrast, time constant of the oxygen uptake (r=-0.500; p=0.034) and buoy turn times (r=-0.525; p=0.027) were negatively associated with performance. SI was the main predictor (R^2=0.495) of open water swimming performance in triathletes. In conclusion, triathletes and coaches must conduct open water training sessions to maximize SI (i.e., swimming efficiency).

Keywords: triathlon, performance, kinematics, energetic, endurance.

INTRODUCTION

Swimming kicks off the first section of a triathlon race, in which athletes must complete the cycling and running subsequent sections consecutively. Since the Sydney 2000 Olympic Games, the Standard distance has been included in the Olympic program, consisting of a 1.5 km swim, 40 km bike and 10 km run [1]. Despite the relatively close inclusion as an Olympic sport, the research focused on triathlon began in the late 1980s [2]. During these years, the scientific literature has focused on analysing different aspects of triathlon, such as pacing strategies [3], physiological [4] or biomechanical parameters [5]. However, the cycling and running sections have received greater attention from the scientific community compared to the swimming section [6], possibly due to the complexity of assessing performance in the aquatic environment [7].

Although early research did not report associations between the swimming section with the final triathlon outcome [8], recent studies have highlighted the importance of this section to increase the chances of success by achieving a strategic position [9,10]. Indeed, this strategic position results in energy expenditure savings due to the drafting effects during swimming [11], which eventually, may affect to the subsequent cycling and running performance [9,12]. In addition to energy expenditure, the main physiological variables that determine triathlon performance are the maximum oxygen uptake ($\dot{V}O_{2max}$), lactate threshold and mechanical efficiency, which have been extendedly studied in the cycling and running sections compared to the swimming section [13]. Recently, the physiological responses of triathletes in a 1500 m pool swimming test has been analysed, showing that those with better performance presented the lowest energy expenditure and peak oxygen uptake ($\dot{V}O_{2peak}$) values. Hence, this study suggested that the faster triathletes are more efficient than less skilled in a 1500 m swimming pool test [7]. Nevertheless, the swimming section still requires further research, especially in natural open water environments where the international triathlon events are held.

Biomechanical swimming parameters are related to the swimmers' technical ability, especially the role attached by the stroke variables [14,15]. Indeed, previous studies suggested the stroke length (SL) as a biomechanical variable to assess the skill enhancement in triathletes [16,17], where the most skilled usually present higher SL and lower stroke rate (SR) values than less skilled triathletes [16,17]. Moreover, the stroke index (SI) is considered an indirect estimation of the swimming efficiency, due to its negative association with energy expenditure [18]. Therefore, a better swimming efficiency, related to higher SL [16] and SI values [7], may significantly influence triathletes' swimming performance. Indeed, these results have been previously observed; however, the aforementioned work was conducted under steady swimming pool conditions [7]. Consequently, considering the biomechanical fluctuations inherent in open water and their impact on swimmers' physiological responses [19] it is crucial to investigate the associations between biomechanical variables (e.g., stroke variables) and physiological responses in competitive triathlon environments. This exploration would contribute to a deeper understanding of swimming performance, particularly considering its potential implications for subsequent cycling and running disciplines.

Swimming is the only triathlon discipline that is mostly trained in a non-competitive environment (i.e., swimming pool), in which performance may be influenced by the turns, push off or gliding [7]. However, the swimming section of a Standard distance triathlon takes place in natural open water environments, such as oceans, rivers or lakes, where changing conditions are challenging [20]. Hence, swimming performance may be affected by the open water characteristics, as observed in long distance swimmers in previous research [19]. In this regard, the information provided in real competitive places may be useful for triathletes and coaches, since it would allow them to know the biomechanical and physiological demands in open water swimming. In this way, coaches may organize their open water training with greater knowledge about triathletes' performance and its demands. However, no research has studied yet triathletes' swimming performance in natural competitive scenarios. Therefore, the aims of the current study were (i) to analyse the 1500 m open water swimming performance, (ii) to examine the associations between physiological and biomechanical variables with swimming performance and (iii) to determine which variables can predict the 1500 m open water swimming performance in triathletes. Based on previous research, it was hypothesised that swimming performance would be influenced by the open water conditions. Due to its negative association with energy expenditure, the fastest triathletes in the 1500 m open water swimming would display a better swimming efficiency, exhibiting higher SI values. Moreover, the SI could predict the open water swimming performance.

METHODS

Participants

Fourteen elite triathletes (10 males and 4 females) volunteered to participate in the current study (Table 1). Among the participants, 1 World Class, 9 Elite/International Level and 4 Highly Trained/National Level were included [21]. Triathletes trained in the same squad under the supervision of the same certified coach. The protocol was explained to the participants before providing written consent to participate, being approved by the University Ethics Committee (*Removed for anonymity*) and conducted in accordance with the Declaration of Helsinki.

Design

The cross-sectional study took place during a summer training camp. The average weekly training time (i.e., three disciplines) was 15.8 ± 2.7 h, while the maximum was 26.8 ± 3.2 h. The recovery times during the sessions and the resistance training were not included as training time. The training load was calculated for all participants using objective load equivalents (ECOs) model [22], obtaining 1354 ± 184 and 2046 ± 293 ECOs weekly average and maximum, respectively. The ECOs model quantifies the training load in triathlon, considering the time in each intensity zone (i.e., from 1 to 10), multiplied by an intensity factor (i.e., from 1 to 300) and by an exercise factor or mode of locomotion (e.g. swimming or running). Triathletes were measured on a single testing session randomly divided to perform the test on two different days under similar conditions. The 1500 m open water swimming test were conducted individually with in-water start, preceded by a 1000 m open water standardized warm-up [23]. Participants used their competition tri-suit (i.e., no wetsuit) and completed the open water swimming test at race pace [3]. During the test, no feedback or encouragement was provided. Participants were asked to refrain from intense exercise at least 24 hours before the testing day. The swimming tests were conducted in a lake with 26.8-27.5ºC water temperature, 29.4-31.2ºC air temperature, 12-16% humidity and 10-14 km/h northwest wind during both days. The wind direction was favorable to the triathletes during odd laps and opposite during even laps (Figure 1).

Methodology

Anthropometric variables were measured for each participant in the same conditions. Body height and body mass were measured using a stadiometer/scale (Seca 799, Hamburg, Germany). Body mass index (BMI) was calculated as body mass (kg)/height $(m)^2$. After the standardized warm-up, triathletes rested 15 min before performing the 1500 m open water swimming test. Oxygen uptake ($\dot{V}O_2$) was continuously measured during 5 min before (baseline) and after the test in sitting position. During recovery period (i.e., off-kinetics), mask fitting was right after completing the last stroke of the test [23]. Respiratory gas exchange was measured breath by breath using a portable gas analyser (Cosmed K5, Rome, Italy). Prior to the tests, air, flowmeter, reference gas, scrubber and time delay calibrations were performed following manufacturers' recommendations. The off-kinetics response was modelled with VO_2FITTING, a free and open-source software [24] based on the R language (www.r-project.org, R Core Team 2015) with support of the "Shiny package" [25]. Raw data were used in all the cases. Bootstrapping with 1000 samples was used to estimate $\dot{V}O_2$ kinetics parameters. Besides, breath-by-breath data obtained during 5 min of recovery were adjusted as a function of time using mono exponential model using the following equation [24]:

$$\dot{V}O_2(t) = EE\dot{V}O_2 - H\left(t - TD_p\right) A_P\left(1 - e^{-(t-TD_p)/\tau_p}\right) \quad (1)$$

where $\dot{V}O_2(t)$ represents the relative $\dot{V}O_2$ at the time t, $EE\dot{V}O_2$ is the $\dot{V}O_2$ at the end of exercise (i.e., 1500 m swimming test), H represents the Heaviside step function [26], and A_p, TD_p and τ_p are the amplitude, time delay and time constant of the $\dot{V}O_2$ fast component [24]. The $EE\dot{V}O_2$ was estimated by backward extrapolation at zero recovery time using linear regressions applied to the first 20 s of recovery [27].

Heart rate (HR) was recorded using a Polar H10 sensor chest strap device (Polar Electro Oy, Kempele, Finland) during the test. Moreover, HR was recorded during the 5 min preceding and following the effort in a seated position. HR recordings were exported from the Polar Flow website to an Excel spreadsheet. Then, mean baseline HR ($HR_{meanBase}$), mean HR during the test ($HR_{mean1500}$), maximum HR during the test ($HR_{max1500}$) and mean HR after the test ($HR_{meanPost}$) were obtained. Blood lactate concentrations $[La^-]$ were collected with a portable lactate analyser (Lactate Pro 2.0, Arkray Inc., Japan) from the swimmers' right lobe 1 min prior to the test and right after the effort, at minute 1 and every 2 min until the peak was reached [7]. Moreover, rate of perceived exertion (RPE) was asked to the swimmers right after the test (0-10 scale) [28]. The Ana_{alac} was estimated from the maximal phosphocreatine splitting in the contracting muscle [29]. It was expressed in kJ assuming an energy equivalent of 0.468 kJ mM and a phosphate/oxygen ratio of 6.25 [30]. The Ana_{lact} energy was calculated using the following equation:

$$Ana_{lact} = [La^{-}]_{net} \cdot \beta \cdot M \qquad (2)$$

where $[La^{-}]_{net}$ is the difference between the $[La^{-}]$ after and before the exercise ($[La^{-}]_{peak}$), β is the constant for O_2 equivalent of $[La^{-}]_{net}$ ($2.7\ ml \cdot kg^{-1} \cdot mM^{-1}$) [31], and M is the body mass of the swimmers. Both energy systems were then expressed in kJ assuming an energy equivalent of $20.9\ kJ \cdot L^{-1}$ [32]. The methods used (i.e., off-kinetics and backward extrapolation) have been previously validated in the scientific literature, specifically in the swimming area [27,33]. However, considering the calculation of the aerobic component as the time integral of the net $EE\dot{V}O_2$ vs. time relationship [30], the swimming speed fluctuations in the 1500 m open water tests may lead to an overestimations of these values [27]. Hence, the aerobic contribution and the variables related to it were discarded from the analysis.

The open water swimming tests were recorded with a Sony FDR-AX53 (Sony Electronics Inc) at 50 Hz sampling rate. Videos were analysed on an in-house customized software for race analysis in competitive swimming by one expert evaluator (i.e., specialist in race analysis, member of a national performance analysis team) [7]. For the 1500 m open water circuit measurement, a 250 m length rope was placed with small floats every five metres and two big buoys at each end. The participants completed the 1500 m swimming test with three 500 m rounds (i.e., rope round trip) with five 180º turns, leaving the buoys always on the left side. For an in-depth biomechanical analysis, each 500 m round were divided in two laps of 250 m, obtaining a total of six laps of 250 m for its assessment (Figure 1). The buoy turn times (s) were calculated from the moment the swimmers' head was next to the buoy and finished the same way in the opposite direction, after the 180º turn. The intraclass correlation coefficient was computed to verify the agreement between repeated measures for each test, obtaining an almost perfect correlation (intraclass correlation coefficients: 0.902 - 0.999). Swimming performance was considered using the World Aquatics Points [34] to standardise the performance times (min:s) obtained in the 1500 m test for male and female triathletes [35], which allows to establish correlations regardless of sex. The swimming speed ($m \cdot s^{-1}$) was measured as the time to cover the distance between the two competition buoys (i.e., 250 m) excluding the buoy turn times. Moreover, the SR was obtained by considering three upper limb cycles divided by the time elapsed during this action and multiplied by sixty to consider the number of cycles per minute. The SR was measured two times every 50 m of each lap (i.e., ten times per 250 m) to obtain the SR in each 250 m lap. The SL was obtained from the ratio between the swimming speed and SR. The SI was calculated as the product of swimming speed and SL [18].

Please insert Figure 1 here

Statistical Analysis

The normality of the distribution was checked with Shapiro-Wilk test. Mean and standard deviation (SD) for descriptive analysis were obtained for all variables. Repeated measures analysis of variance (ANOVA) differentiating by sex, was used to assess the change in performance and biomechanical variables every lap during the 1500 m open water swimming test and Bonferroni post-hoc was used to check differences between each 250 m lap and the respective mean value of the variable during the test (i.e. 1500 m). For the ANOVA effect size index, the eta squared (η^2) was computed and interpreted as: $0 < \eta^2 < 0.04$ without effect; $0.04 < \eta^2 < 0.25$ minimum; $0.25 < \eta^2 < 0.64$ moderate; $\eta^2 > 0.64$ strong [36]. Pearson's Correlation Coefficient was computed to analyse the associations between World Aquatics Points (i.e., swimming performance) with the physiological and biomechanical variables. Due to the small sample size, the correlation and regression analysis were performed without differentiating by sex. For that reason, World Aquatics Points were used to standardize the swimming performance and to perform the correlation analyses with both sexes. Stepwise multivariate regression analysis was applied including only the variables that showed significant association with swimming performance to determine the strongest predictors in open water swimming. Regression analyses were performed including and excluding the swimming speed due to its direct and high positive correlation with swimming performance [7]. Moreover, the possibility of collinearity and multicollinearity in the multiple regression models was examined using the variance inflation factor (VIF). 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 [37]. To verify the correlation and regression analyses, a network analysis was conducted [38]. Following the procedures in previous swimming research [39], measures of centrality (i.e., betweenness, closeness and strength centrality) were calculated to identify the role of each variable correlation, transforming the values into a z-score [39]. The network analysis was conducted in the RStudio software (RStudio Inc., Boston, MA) and the "*qgpraph*" package was used to develop the figure [38]. The significance level was set up at $p < 0.05$ and the rest of the statistical analyses were conducted using the Statistical Package for the Social Sciences (SPSS 28.0, IBM Corporation Chicago, IL, USA).

RESULTS

Descriptive statistics are presented in Table 1. Changes and differences between 250 m laps and mean values of the biomechanical variables for each sex are shown in Figure 2. In male triathletes, the highest values in all biomechanical variables were obtained in the first 250 m (Figure 2, left panels). There were reductions in swimming speed ($\eta^2 = 0.75$; $p < 0.001$), SI ($\eta^2 = 0.66$; $p < 0.001$) and SL ($\eta^2 = 0.47$; $p < 0.001$). Instead, higher SR ($\eta^2 = 0.54$; $p < 0.001$) was observed in the first 250 m (Figure 2, left panels). On the other hand, females only showed a decrease in SL ($\eta^2 = 0.82$; $p < 0.001$) in the last 250 m (Figure 2, right panels).

Please insert Table 1 here

Please insert Figure 2 here

Pearson's correlations showed positive associations between World Aquatics Points (i.e., swimming performance) and $EE\dot{V}O_2$ (moderate, r = 0.513; $p = 0.030$), while τ_p presented negative associations (moderate, r = -0.500; $p = 0.034$). Regarding biomechanical variables, swimming speed (very large, r = 0.873; $p < 0.001$) and SI (large, r = 0.704; $p = 0.002$) were positive associated with swimming performance, while buoy turn time presented negative relationships (moderate, r = -0.525; $p = 0.027$).

The stepwise multiple regression showed that the 76% of the variance of swimming performance was explained by swimming speed ($R^2 = 0.762$, adjusted $R^2 = 0.742$). The VIF calculated for all regression was always below 2.5, indicating a lack of collinearity. However, when excluding swimming speed in the analysis, SI emerged as the main predictor for swimming performance, explaining 50% of the variance in swimming performance ($R^2 = 0.495$, adjusted $R^2 = 0.453$). This second model was selected, due to the high correlation between swimming performance and swimming speed observed in the first model. The raw and standardised regression coefficients and partial correlations of the predictors are presented in Table 2.

Please insert Table 2 here

The network of associations between World Aquatics Points (i.e., swimming performance) and physiological and biomechanical variables are shown in Figure 3. The representation displayed the positive associations between swimming performance with swimming speed and SI. Certainly, SI exhibited a central position in the network, obtaining the highest z-score in the centrality measures (Table 3).

Please insert Figure 3 here

Please insert Table 3 here

DISCUSSION

The aims of the present study were to analyse the 1500 m open water swimming performance, to examine the relations between physiological and biomechanical variables with swimming performance and to determine which variables can predict the performance. The main findings of this study corroborated the hypothesis that swimming performance was affected by the open water conditions. Moreover, triathletes with better swimming performance were more efficient, exhibiting higher SI values than less skilled triathletes. In addition, when excluding swimming speed, the SI was the main predictor of 1500 m open swimming performance for elite triathletes.

The initial meters of the swimming section in a triathlon race are the fastest to achieve a strategical position [3]. Regarding males, this was observed in the results obtained, since triathletes were asked to complete the test following the same strategy performed in real events (Figure 2, left panel). Moreover, the highest values of the stroke variables (i.e., SR, SL and SI) were obtained in these initial meters of the open water swimming test. On the other hand, the swimming speed decreased in the fourth and the last 250 m laps (Figure 2, left panel), together with a SL and SI declined. These changes may be explained by the open water environment, affecting swimming speed and stroke variables and how swimmers modify their technique depending of the tides or currents [20]. In fact, as Figure 2 shows, both swimming speed and SI did not follow a linear trend, probably induced by the influence of the currents. In females, no differences were found in swimming speed, SR and SI between each lap and their respective mean values, finding only a significant decrease in SL in the last 250 m (Figure 2, right panel). This could be explained due to fatigue and loss of efficiency in the last part of the test [19], but also by the currents against the triathletes' swimming direction, as explained above. In line with previous studies with long-distance swimmers [15,40], the SL impairment was compensate by an increase in SR to maintain the swimming speed. However, in the case of female triathletes, SR was not significantly different from the mean throughout the race. Yet, it is worth noting that the lack of significant biomechanical changes in females might be explained by low sample size. Thus, future research should try to delve more deeply into the swimming behaviour of female triathletes, who are often underrepresented in triathlon literature. Upon these results, triathletes should find a balance between a fast start that allows them to get a strategic position and to conserve an efficient biomechanics to maintain swimming speed in open water conditions, being essential for the subsequent cycling and running sections.

The analysis of physiological variables in swimming is always a challenge, increasing even more its complexity in an open water environment [19]. In contrast to the negative associations between $\dot{V}O_{2peak}$ and energy expenditure with 1500 m swimming performance shown in previous research [7], the positive correlations between $EE\dot{V}O_2$ and performance obtained in the current study seems to indicate some differences between pool and open water swimming tests. In that sense, differences between $\dot{V}O_{2peak}$ in the pool and $EE\dot{V}O_2$ after the open water test may arise from variations in swimming speed and biomechanical adaptations to the natural environment. Moreover, these higher $EE\dot{V}O_2$ values may be due to the high demands of open water swimming [20] and the differences with swimming pool races (i.e., turns, push off or gliding) [7]. Thus, the continuous arm action in open water compared to the effect of acyclic phases in the pool, may explain these physiological differences. In addition to the aforementioned association, the negative relationship between τ_p and performance may indicate a higher level of aerobic fitness, since endurance performance times (e.g., in cycling or running) has been significantly correlated with τ_p [41]. Moreover, shorter τ_p has been associated with both increased time to exhaustion and fatigue tolerance [42]. Therefore, the shorter τ_p obtained by the best performing triathletes may highlight a better coordination between the cardiorespiratory and muscular systems in the fastest triathletes [41], responding faster to energy demands than triathletes with lower swimming performance.

Regarding biomechanical variables, swimming speed and SI presented positive associations with swimming performance, matching previous results in a 1500 m front-crawl swimming pool test with triathletes [7]. The high correlation between the swimming speed and performance is evident, as speed is an essential factor in open water swimming [43]. Moreover, considering the SI as an indirect estimation for the swimming efficiency [18], the positive association between SI and performance could explain the more efficient technique of the fastest triathletes. Hence, triathletes must focus on maximizing the SI, in which the SL maintenance also plays an essential role [16], as SI is the product of swimming speed and SL [18]. On the other hand, the negative correlations between the buoy turn times and swimming performance showed that the fastest triathletes also obtained the shortest time to complete the buoy turn. Although it has not been previously studied, the turn analysis was included to obtain an accurate swimming speed of each lap and, also, to discern if these buoy turns affect the overall swimming performance. However, the lack of real competition circumstances must be acknowledged, as during the races triathletes face the buoy turns with other opponents and speed variations from positioning against other triathletes may influence the open water swimming performance.

Performance analysis and predictive model in Standard distance triathlon reported the relevance of finishing the swimming section close to the leader [44]. Hence, increasing the knowledge and how to achieve enhancements in the swimming discipline is crucial for triathletes' success. The model obtained in the current study determined the SI as the main predictor variable for the open water swimming performance. This finding partially aligns with the conclusion of previous study, determining SI and energy expenditure as the predictors in 1500 m swimming pool performance [7]. In this case, the results were not corroborated by the energy expenditure as the calculation of the aerobic component could be overestimated when using off-kinetics method at unstable swimming speeds

[27], thus the total energy expenditure was not considered. However, the indirect estimation of swimming efficiency through the SI may be essential [18], since the ability to manage energy is decisive for triathlon success [3]. On the other hand, considering the World Aquatics Points as the swimming performance variable, and the SI calculation (i.e., product of swimming speed and SL) [18], it is important to highlight the close relationships between World Aquatic Points, swimming speed and SI, also revealed by the network analysis (Figure 3, Table 3). The relationship between these variables might have influenced the correlation and regression analyses results. Nevertheless, the VIF results in our models indicated the non-existence of collinearity or multicollinearity between the predictors. Thus, considering the results obtained in the current study and partially agreeing with previous research in swimmers [45], triathletes must optimize their efficiency through the stroke variables (i.e., technical skills), trying to maximize the SI values.

To the best of the authors' knowledge, there is no previous study that investigated the open water swimming in triathletes, hence the results obtained may have great relevance for coaches and athletes. One of the limitations of the current study was the small sample size, especially of females. Nevertheless, it is important to highlight the high level of the participants and the controlled condition (i.e., same squad and coach). Moreover, the 180º turns performed during the 1500 m open water swimming are unusual in a triathlon competition; yet, this procedure was followed to increase the accuracy of the biomechanical variables. On the other hand, the competitive situations approach should be considered (e.g., swimming alone vs. swimming with opponents or swimming before the cycling and running sections), as these circumstances may differ from the results obtained in the current study. Future research should analyse open water swimming performance with on-kinetics method, considering the aerobic contribution and total energy expenditure. Moreover, large samples with participants of different performance levels should be considered. Based on the current results, triathletes and coaches should include specific open water training sessions, as it is the competitive environment and may affect swimming biomechanics. In addition, technical skills must be promoted and quantified in training in order to optimize the swimming efficiency for increasing the successful coping in the following cycling and running sections.

CONCLUSIONS

The analysis of the 1500 m open water swimming performance showed the highest values of biomechanical variables (i.e., swim speed, SR, SL and SI) in the initial meters in males, while a decrease in SL was observed in the last meters in both sexes. The fastest triathletes in 1500 m open water swimming obtained the highest $EE\dot{V}O_2$ and the lowest τ_p values, exhibiting better efficiency through higher SI values. Indeed, the SI was the main predictor for the 1500 m open water swimming performance in triathletes.

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DISCLOSURE STATEMENT

No potential conflicts of interest was reported by the authors.

REFERENCES

[1] World Triathlon. World Triathlon Competition Rules 2023. 2023; Internet: https://www.triathlon.org/about/downloads/category/competition_rules; accessed: 01/05/2023

[2] Van Rensburg JP, Kielblock AJ, Van Der Linde A. Physiologic and biochemical changes during a triathlon competition. Int J Sports Med 1986; 7: 30–35. doi:10.1055/s-2008-1025731

[3] Vleck VE, Bentley DJ, Millet GP, et al. Pacing during an elite Olympic distance triathlon: Comparison between male and female competitors. J Sci Med Sport 2008; 11: 424–432. doi:10.1016/j.jsams.2007.01.006

[4] Bentley DJ, Millet GP, Vleck VE, et al. Specific aspects of contemporary triathlon: Implications for physiological analysis and performance. Sport Med 2002; 32: 345–359

[5] Olaya-Cuartero J, Cejuela R. Influence of biomechanical parameters on performance in elite triathletes along 29 weeks of training. Appl Sci 2021; 11: 1–

12. doi:10.3390/app11031050

[6] Peeling P, Landers G. Swimming intensity during triathlon: A review of current research and strategies to enhance race performance. J Sports Sci 2009; 27: 1079–1085. doi:10.1080/02640410903081878

[7] López-Belmonte Ó, Ruiz-Navarro JJ, Gay A, et al. Determinants of 1500-m Front-Crawl Swimming Performance in Triathletes: Influence of Physiological and Biomechanical Variables. Int J Sports Physiol Perform 2023; 18: 1328–1335. doi:10.1123/ijspp.2023-0157

[8] Dengel DR, Flynn MG, Costill DL, et al. Determinants of success during triathalon competition. Res Q Exerc Sport 1989; 60: 234–238. doi:10.1080/02701367.1989.10607445

[9] Vleck VE, Bürgi A, Bentley DJ. The consequences of swim, cycle, and run performance on overall result in elite olympic distance triathlon. Int J Sports Med 2006; 27: 43–48. doi:10.1055/s-2005-837502

[10] Landers GJ, Blanksby BA, Ackland TR, et al. Swim Positioning and its Influence on Triathlon Outcome. Int J Exerc Sci 2008; 1: 96–105

[11] Bentley DJ, Libicz S, Jougla A, et al. The effects of exercise intensity or drafting during swimming on subsequent cycling performance in triathletes. J Sci Med Sport 2007; 10: 234–243. doi:10.1016/j.jsams.2006.05.004

[12] Cejuela R, Cala A, Pérez-Turpin JA, et al. Temporal activity in particular segments and transitions in the olympic triathlon. J Hum Kinet 2013; 36: 87–95. doi:10.2478/hukin-2013-0009

[13] Millet GP, Vleck VE, Bentley DJ. Physiological requirements in triathlon. J Hum Sport Exerc 2011; 6: 184–204

[14] Zamparo P, Cortesi M, Gatta G. The energy cost of swimming and its determinants. Eur J Appl Physiol 2020; 120: 41–66

[15] López-Belmonte Ó, Ruiz-Navarro JJ, Gay A, et al. Analysis of pacing and kinematics in 3000 m freestyle in elite level swimmers. Sport Biomech 2023; 1–17. doi:10.1080/14763141.2023.2184418

[16] Millet GP, Chollet D, Chalies S, et al. Coordination in front crawl in elite triathletes and elite swimmers. Int J Sports Med 2002; 23: 99–104. doi:10.1055/s-2002-20126

[17] Toussaint HM. Differences in propelling efficiency between competitive and triathlon swimmers. Med Sci Sports Exerc 1990; 22: 409–415. doi:10.1249/00005768-199006000-00020

[18] Costill DL, Kovaleski J, Porter D, et al. Energy expenditure during front crawl swimming: Predicting success in middle-distance events. Int J Sports Med 1985; 6: 266–270. doi:10.1055/s-2008-1025849

[19] 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: 2005–2018. doi:10.1007/s00421-020-04420-7

[20] Baldassarre R, Bonifazi M, Zamparo P, et al. Characteristics and challenges of open-water swimming performance: A review. Int J Sports Physiol Perform 2017;

12: 1275–1284

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

[22] Cejuela R, Esteve-Lanao J. Quantifying the Training Load in Triathlon. In: Triathlon Medicine. Springer International Publishing; 2020: 291–316

[23] Ruiz-Navarro JJ, Gay A, Zacca R, et al. Biophysical Impact of 5-Week Training Cessation on Sprint Swimming Performance. Int J Sports Physiol Perform 2022; 17: 1463–1472. doi:10.1123/ijspp.2022-0045

[24] Zacca R, Azevedo R, Figueiredo P, et al. Vo2fitting: A free and open-source software for modelling oxygen uptake kinetics in swimming and other exercise modalities. Sports 2019; 7. doi:10.3390/sports7020031

[25] Chang W, Cheng J, Allaire J, Xie Y MJ. Shiny: web application framework for R. 2015. . Internet: http://cran.r-project.org/package=shiny; accessed: 01/05/2023

[26] Ma S, Rossiter. HB, Barstow. TJ, et al. Clarifying the equation for modeling of V̇o2 kinetics above the lactate threshold. J Appl Physiol 2010; 109: 1283–1284

[27] Monteiro AS, Carvalho DD, Azevedo R, et al. Post-swim oxygen consumption: Assessment methodologies and kinetics analysis. Physiol Meas 2020; 41. doi:10.1088/1361-6579/abb143

[28] Borg GAV. Psychophysical bases of perceived exertion. Med Sci Sports Exerc 1982; 14: 377–381

[29] Sousa A, Figueiredo P, Pendergast D, et al. Critical evaluation of oxygen-uptake assessment in swimming. Int J Sports Physiol Perform 2014; 9: 190–202. doi:10.1123/IJSPP.2013-0374

[30] Zamparo P, Capelli C, Pendergast D. Energetics of swimming: A historical perspective. Eur J Appl Physiol 2011; 111: 367–378. doi:10.1007/s00421-010-1433-7

[31] Thevelein X, Daly D, Persyn U. Measurement of total energy use in the evaluation of competitive swimmers. In: Bachl N, Prakop L, Suckaert R, eds. Current Topics in Sports Medicine. Wien: Urban & Schwartzenberg; 1984: 668–676

[32] Di Prampero PE, Ferretti G. The energetics of anaerobic muscle metabolism: A reappraisal of older and recent concepts. Respir Physiol 1999; 118: 103–115. doi:10.1016/S0034-5687(99)00083-3

[33] Rodriguez F, Chaverri D, Iglesias X, et al. Validity of postexercise measurements to estimate peak VO2 in 200-m and 400-m maximal swims. Int J Sports Med 2017; 38: 426–438. doi:10.1055/s-0042-123707

[34] World Aquatics. World Aquatics Points, united by water 2023. 2023; Internet: https://www.worldaquatics.com/SWIMMING/POINTS; accessed: 01/05/2023

[35] Ruiz-Navarro JJ, López-Belmonte Ó, Gay A, et al. A new model of performance classification to standardize the research results in swimming. Eur J Sport Sci 2023; 23: 478–488. doi:10.1080/17461391.2022.2046174

[36] Ferguson C. An effect size primer: a guide for clinicians and researchers. Prof Psychol Res Pract 2009; 40: 532–538. doi:https://doi.org/10.1037/a0015808

[37] Hopkins WG, Marshall SW, Batterham AM, et al. Progressive statistics for studies in sports medicine and exercise science. Med Sci Sports Exerc 2009; 41: 3–12

[38] Epskamp S, Cramer AOJ, Waldorp LJ, et al. Qgraph: Network visualizations of relationships in psychometric data. J Stat Softw 2012; 48: 1–18. doi:10.18637/jss.v048.i04

[39] Fiori JM, Bandeira PFR, Zacca R, et al. The Impact of a Swimming Training Season on Anthropometrics, Maturation, and Kinematics in 12-Year-Old and Under Age-Group Swimmers: A Network Analysis. Front Sport Act Living 2022; 4. doi:10.3389/fspor.2022.799690

[40] Morais JE, Barbosa TM, Forte P, et al. Stability analysis and prediction of pacing in elite 1500 m freestyle male swimmers. Sport Biomech 2023; 22: 1496–1513. doi:10.1080/14763141.2020.1810749

[41] Reis JF, Alves FB, Bruno PM, et al. Oxygen uptake kinetics and middle distance swimming performance. J Sci Med Sport 2012; 15: 58–63. doi:10.1016/j.jsams.2011.05.012

[42] Demarle AP, Slawinski JJ, Laffite LP, et al. Decrease of O2 deficit is a potential factor in increased time to exhaustion after specific endurance training. J Appl Physiol 2001; 90: 947–953. doi:10.1152/jappl.2001.90.3.947

[43] Baldassarre R, Pennacchi M, La Torre A, et al. Do the fastest open-water swimmers have a higher speed in middle- and long-distance pool swimming events? J Funct Morphol Kinesiol 2019; 4: 1–15. doi:10.3390/jfmk4010015

[44] Ofoghi B, Zeleznikow J, Macmahon C, et al. Performance analysis and prediction in triathlon. J Sports Sci 2016; 34: 607–612. doi:10.1080/02640414.2015.1065341

[45] Fernandes RJ, Vilas-Boas JP. Time to exhaustion at the VO2max velocity in swimming: A review. J Hum Kinet 2012; 32: 121–134

TABLE AND FIGURE CAPTIONS

Table 1. Mean ± Standard deviation (SD) of physical characteristics, performance, physiological and biomechanical variables of elite triathletes.

Table 2. Summary of model selected based on stepwise multiple regression analysis for the 1500 m open water swimming performance of elite triathletes (n = 14).

Table 3: Z-score obtained for the betweenness, closeness and strength centrality measures between performance, physiological and biomechanical variables.

Figure 1. Visual representation of the open water swimming circuit and the assessment of physiological variables.

Figure 2. Biomechanical changes for male (n = 10; left panels) and female triathletes (n= 4; right panels) during the 1500 m open water swimming test. Significant differences between 250 m laps and the respective mean value of each variable are represented (# $p < 0.05$; * $p < 0.001$).

Figure 3. Network analysis of correlations between swimming performance, physiological and biomechanical variables in elite triathletes (n = 14). The positive and negative relationships are represented in green and red, respectively. The thickness and intensity of the colors indicate the magnitude of the associations. $HR_{mean1500}$ = mean heart rate during the test; $HR_{max1500}$ = maximum heart rate during the test; $HR_{meanPost}$ = mean heart rate after the test; $[La^{-}]_{peak}$ = peak blood lactate concentration; $[La^{-}]_{net}$ = lactate concentration difference between the $[La^{-}]_{peak}$ and $[La^{-}]_{Base}$; $EE\dot{V}O_2$ = end-exercise oxygen uptake; RER = respiratory exchange ratio; A_p, TD_p and τ_p = amplitude, time delay and time constant of the oxygen uptake fast component; Ana_{alac} and Ana_{lact} = anaerobic alactic and anaerobic lactic contributions; SR, SL and SI = stroke rate, length and index.

Table 1. Mean ± Standard deviation (SD) of physical characteristics, performance, physiological and biomechanical variables of elite triathletes.

	Male triathletes (n = 10)	Female triathletes (n = 4)	Total sample (n = 14)
Variable	Mean ± SD	Mean ± SD	Mean ± SD
Physical characteristics			
Age (years)	23.24 ± 3.70	23.63 ± 4.47	23.36 ± 3.76
Body height (cm)	177.50 ± 6.62	169.75 ± 10.56	175.29 ± 8.32
Body mass (kg)	66.73 ± 7.48	58.30 ± 8.72	64.32 ± 8.48
Body mass index ($kg \cdot m^{-2}$)	21.12 ± 1.08	20.13 ± 1.05	20.84 ± 1.13
Performance variables			
T0-500 (min:s)	6:36 ± 0:15	7:10 ± 0:11	6:46 ± 0:21
T500-1000 (min:s)	6:50 ± 0:18	7:24 ± 0:12	6:59 ± 0:22
T1000-1500 (min:s)	6:50 ± 0:21	7:28 ± 0:15	7:01 ± 0:26
T1500 (min:s)	20:17 ± 0:53	22:01 ± 0:37	20:46 ± 1:08
World Aquatics Points	369 ± 49	339 ± 29	360 ± 45
Physiological variables			
$HR_{meanBase}$ ($beats \cdot min^{-1}$)	76 ± 19	83 ± 10	78 ± 17
$HR_{mean1500}$ ($beats \cdot min^{-1}$)	166 ± 11	167 ± 4	166 ± 10
$HR_{max1500}$ ($beats \cdot min^{-1}$)	174 ± 12	175 ± 2	175 ± 10
$HR_{meanPost}$ ($beats \cdot min^{-1}$)	113 ± 11	119 ± 2	115 ± 10
$[La^-]_{Base}$ ($mmol \cdot L^{-1}$)	2.37 ± 0.41	2.05 ± 0.31	2.29 ± 0.40
$[La^-]_{peak}$ ($mmol \cdot L^{-1}$)	7.49 ± 1.58	7.43 ± 2.56	7.47 ± 1.80
$[La^-]_{net}$ ($mmol \cdot L^{-1}$)	5.12 ± 1.54	5.38 ± 2.47	5.19 ± 1.75
$EE\dot{V}O_2$ ($ml \cdot kg^{-1} \cdot min^{-1}$)	56.98 ± 7.47	48.65 ± 5.56	54.60 ± 7.81
RER	1.05 ± 0.13	0.92 ± 0.04	1.01 ± 0.13
A_p ($ml \cdot kg^{-1} \cdot min^{-1}$)	46.63 ± 7.89	40.05 ± 4.33	44.75 ± 7.55
TD_p (s)	5.56 ± 8.38	8.31 ± 9.31	6.35 ± 8.38
τ_p (s)	41.02 ± 6.88	48.68 ± 13.83	43.20 ± 9.48
Ana_{alac} (kJ)	27.73 ± 3.11	24.23 ± 3.62	26.73 ± 3.52
Ana_{lact} (kJ)	19.42 ± 6.64	17.22 ± 7.53	18.79 ± 6.69
RPE	9.80 ± 0.42	9.00 ± 0.82	9.57 ± 0.65
Biomechanical variables			
Swimming speed ($m \cdot s^{-1}$)	1.24 ± 0.05	1.14 ± 0.03	1.21 ± 0.06
SR ($cycles \cdot min^{-1}$)	40.72 ± 3.03	39.71 ± 1.61	40.43 ± 2.68
SL (m)	1.83 ± 0.15	1.73 ± 0.08	1.80 ± 0.14
SI ($m^2 \cdot s^{-1}$)	2.27 ± 0.23	1.98 ± 0.12	2.19 ± 0.24
Buoy Turn Times (s)	4.54 ± 0.24	5.02 ± 0.66	4.68 ± 0.44

T0-500 = performance time of the first and second laps; T500-1000 = performance time of the third and fourth laps; T1000-1500 = performance time of the fifth and sixth laps; T1500 = time performed in the 1500 m test; $HR_{meanBase}$ = mean baseline heart rate; $HR_{mean1500}$ = mean heart rate during the test; $HR_{max1500}$ = maximum heart rate during the test; $HR_{meanPost}$ = mean heart rate after the test; $[La^-]_{Base}$ = baseline blood lactate concentration; $[La^-]_{peak}$ = peak blood lactate concentration; $[La^-]_{net}$ = lactate concentration difference between the $[La^-]_{peak}$ and $[La^-]_{Base}$; $EE\dot{V}O_2$ = end-exercise oxygen uptake value; RER = respiratory exchange ratio; A_p, TD_p and τ_p = amplitude, time delay and time constant of the oxygen uptake fast component; Ana_{alac} and Ana_{lact}= anaerobic alactic and anaerobic lactic contributions; RPE = rating of perceived exertion; SR, SL and SI = stroke rate, length and index.

Table 2. Summary of model selected based on stepwise multiple regression analysis for the 1500 m open water swimming performance of elite triathletes (n = 14).

Variable	**Raw beta**	**Std. error**	**Std. beta**	***t***	***p* value**	**Partial correlation**
Stepwise multiple regression analysis including swimming speed						
Constant	-392.79	121.65		-3.23	0.007	
Swimming speed ($m \cdot s^{-1}$)	621.52	100.29	0.87	6.20	<0.001	0.873
Stepwise multiple regression analysis excluding swimming speed						
Constant	76.75	83.10		0.92	0.037	
Stroke index ($m^2 \cdot s^{-1}$)	129.53	37.77	0.70	3.43	0.005	0.704

Table 3: Z-score obtained for the betweenness, closeness and strength centrality measures between performance, physiological and biomechanical variables.

	Centrality measures		
	Betweenness	**Closeness**	**Strength**
Performance variable			
World Aquatics Points	-0.61	-1.82	1.24
Physiological variables			
$HR_{mean1500}$	-0.42	-0.38	-0.01
$HR_{max1500}$	-0.61	-0.36	0.06
$HR_{meanPost}$	-0.94	-0.67	1.22
$[La^{-}]_{peak}$	0.59	0.26	-0.59
$[La^{-}]_{net}$	0.16	-0.24	-0.45
$EE\dot{V}O_2$	0.87	0.82	0.62
RER	0.10	0.78	-0.74
A_p	-0.55	-0.04	0.20
TD_p	-0.36	-0.37	-0.22
τ_p	-0.68	-0.71	0.93
Ana_{alac}	-0.48	-0.84	0.05
Ana_{lact}	0.87	-0.03	-0.64
Biomechanical variables			
Swimming Speed	-0.74	-1.68	1.19
SR	-0.76	-0.54	-0.31
SL	-1.01	0.89	1.26
SI	1.21	1.84	1.60
Buoy Turn Times	-0.03	0.59	-0.80

$HR_{mean1500}$ = mean heart rate during the test; $HR_{max1500}$ = maximum heart rate during the test; $HR_{meanPost}$ = mean heart rate after the test; $[La^{-}]_{peak}$ = peak blood lactate concentration; $[La^{-}]_{net}$ = lactate concentration difference between the $[La^{-}]_{peak}$ and $[La^{-}]_{Base}$; $EE\dot{V}O_2$ = end-exercise oxygen uptake; RER = respiratory exchange ratio; A_p, TD_p and τ_p = amplitude, time delay and time constant of the oxygen uptake fast component; Ana_{alac} and Ana_{lact} = anaerobic alactic and anaerobic lactic contributions; SR, SL and SI = stroke rate, length and index.

Figure 1

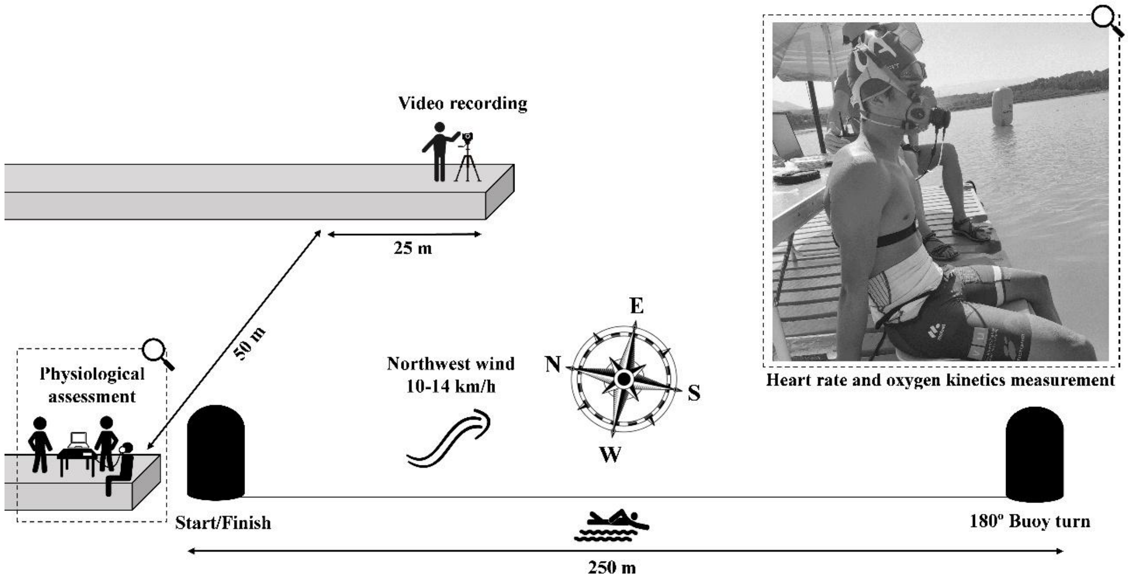
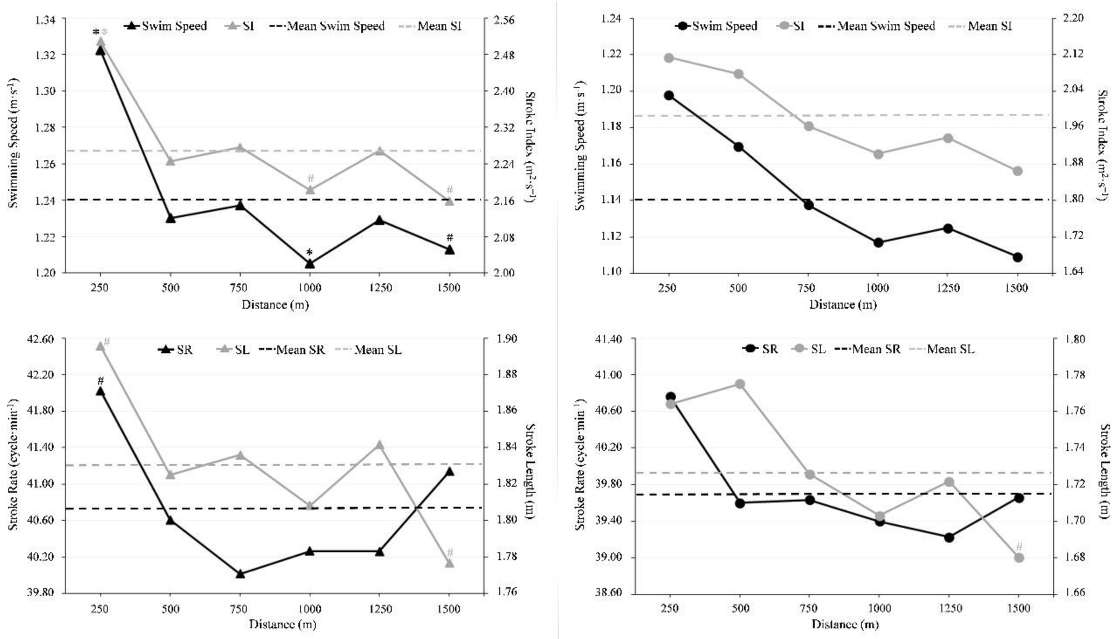
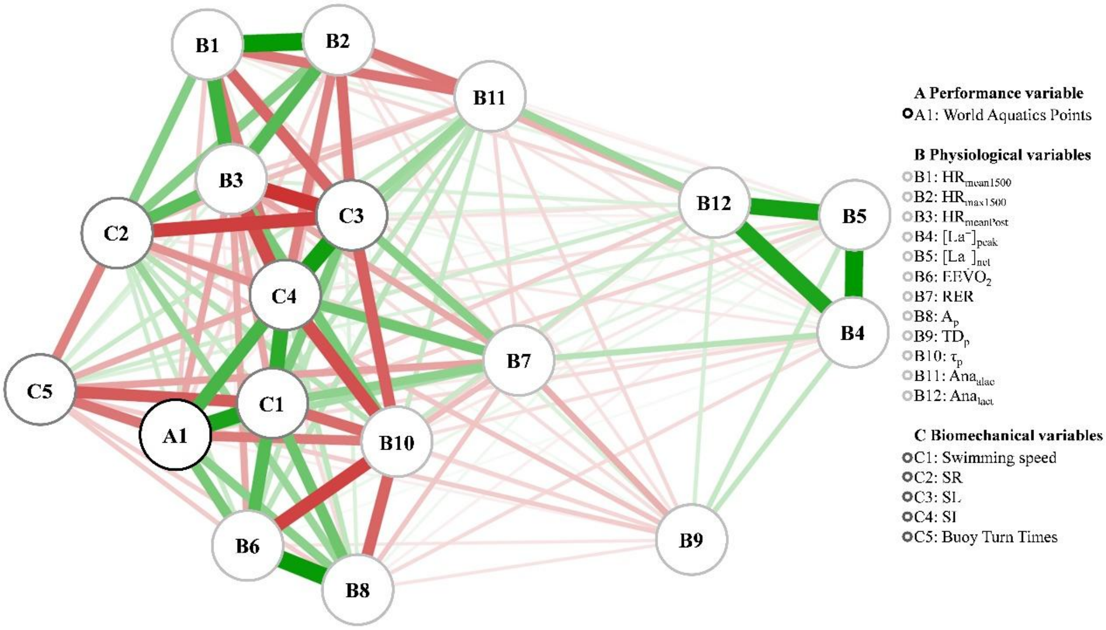

Video recording
25 m
50 m
Physiological assessment
Northwest wind
10-14 km/h
E
N
S
W
Heart rate and oxygen kinetics measurement
Start/Finish
180º Buoy turn
250 m

Figure 2



Swim Speed
SI
Mean Swim Speed
Mean SI
Swimming Speed (m·s-1)
Stroke Index (m2·s-1)
Distance (m)
250
500
750
1000
1250
1500
SR
SL
Mean SR
Mean SL
Stroke Rate (cycle·min-1)
Stroke Length (m)

Figure 3


B1
B2
B11
B3
C3
C2
C4
B12
B5
B4
B7
C5
C1
A1
B10
B6
B8
B9
A Performance variable
A1: World Aquatics Points
B Physiological variables
B1: $HR_{mean1500}$
B2: $HR_{max1500}$
B3: $HR_{meanPost}$
B4: $[La^-]_{peak}$
B5: $[La^-]_{net}$
B6: $EE\dot{V}O_2$
B7: RER
B8: A_p
B9: TD_p
B10: τ_p
B11: Ana_{alac}
B12: Ana_{lact}
C Biomechanical variables
C1: Swimming speed
C2: SR
C3: SL
C4: SI
C5: Buoy Turn Times