Acta Scientiarum
http://periodicos.uem.br/ojs
ISSN on-line: 1807-8648
Doi: 10.4025/actascihealthsci.v46i1.64813

Physiological and biomechanical analyses of a 200 m all-out front crawl

Marcos Franken[1*], Kelly de Jesus[2], Vitória Miranda[2] and Karla de Jesus[2]

[1]Universidade Regional Integrada do Alto Uruguai e das Missões, Rua Pinheiro Machado, 2994, 97700-205, Santiago, Rio Grande do Sul, Brazil.
[2]Universidade Federal do Amazonas, Manaus, Amazonas, Brazil. *Author for correspondence.E-mail: marcos_franken@yahoo.com.br

ABSTRACT. This study aimed to analyze the effort effects of laps on general stroke kinematics and associate the peak oxygen uptake (VO_{2peak}) with all-out 200-m front crawl time. Fourteen regional-level swimmers (age 16.14 ± 2.68 years; height 1.65 ± 0.08 m; body mass 58.17 ± 7.76 kg) performed an all-out 200 m front crawl. Oxygen consumption (VO_2) was measured post-all-out 200 m trial to assess physiological variables and stroke mechanics was assessed based on the time to perform 10 m and time to perform three complete arm stroke cycles. The 1st lap had a higher stroke rate (SR) than the 3rd lap (44.73 vs. 40.82 cycles·min^{-1}; $p = 0.04$). The 1st lap showed a higher mean swimming speed (SS) than the following laps (1.45 ± 0.10 vs. 1.35 ± 0.11 vs. 1.30 ± 0.11 vs. 1.28 ± 0.13 m·s^{-1}; $p < 0.01$) and the 2nd was greater than the 4th lap ($p < 0.05$). The swimming index (SI) was smaller and greater in the 3rd lap compared to the 1st and 4th laps (2.60 ± 0.65 vs. 2.97 ± 0.71 vs. 2.43 ± 0.50 m^2·s^{-1}·cycles^{-1}), respectively. There was moderate and inverse coefficient of correlation between the VO_{2peak} and 200-m time (rho = -0.653; $p < 0.05$). Our findings suggest that VO_{2peak} values should be assessed in post 200-m all-out effort due to the strong shared variance with performance and a pacing strategy should be adopted during the race to avoid detrimental effects of fatigue.

Keywords: aerobic power; post-exercise VO_2; swimming; middle-distance.

Received on August 27, 2022
Accepted on January 25, 2023

Introduction

Swimming performance depends on anthropometric, psychological, environmental, biomechanical, and physiological factors(Barbosa et al., 2010a; Figueiredo, Zamparo, Sousa, Vilas-Boas, & Fernandes, 2011), among whichthe physiological and biomechanical aspects are the most investigated and controlled (Figueiredo et al., 2011; Monteiro et al., 2020). Competitive swimming performance depends on the swimmer's maximal metabolic power (aerobic energy sources; Rodríguez, Chaverri, Iglesias, Schuller, & Hoffmann, 2017). Hence, the maximal oxygen uptake ($\dot{V}O_{2max}$) is considered an important performance factor that expresses maximal aerobic power. Assessing cardiopulmonary gas exchange and oxygen uptake (VO_2) in swimming is a complex and cumbersome procedure that involves limitations imposed by the water environment and the equipment (Fernandes et al., 2012; Chaverri, Schuller, Iglesias, Hoffman, & Rodríguez, 2016). From a technical standpoint, the following two main indirect calorimetry approaches have been used to collect and analyze expiratory gases in swimming: (I) measurements during exercise using snorkels with built-in valves connected to Douglas bags (Holmer, 1972), open-circuit metabolic carts(Fernandes et al., 2003) or breath-by-breath portable gas analyzers (Fernandes, et al., 2012; de Jesus et al., 2015) and (II) post-exercise measurements with gas collection via face mask or mouthpiece connected to Douglas bags or open-circuit metabolic carts (Rodríguez et al., 2017).

The VO_2 post-exercise measurements (i.e. gas collection after swimming only) by estimating the peak oxygen uptake ($\dot{V}O_{2peak}$) and the oxygen uptake efficiency slope (OUES) has been pointed out as a good surrogate replacing the role of VO_{2peak} to assess cardiorespiratory fitness in samples that cannot attain maximal effort (Han et al., 2021). Therefore, VO_2 post-exercise measurement can be applied to maximal tests in field conditions where the annoying valve system could affect the performance and improve the estimationerror (Leger, Seliger, & Brassard, 1980; Chaverri et al., 2016; Rodríguez et al., 2017). The post-exercise VO_2 measurements during a 200-m all-out swim allowed us to estimate exercise $\dot{V}O_{2peak}$ in elite competitive swimmers with good accuracy (Chaverri et al., 2016). Estimating post-exercise VO_{2peak} allows swimmers to perform completely unrestricted (i.e., without a mouthpiece, snorkel, or tubing), which is a clear advantage for pool testing and research provided that $\dot{V}O_2$ can be estimated with sufficient accuracy (Rodríguez et al., 2017). The VO_{2peak} proved to be very closely related to short- (100-m; $r^2 = 0.62$) and middle-distance events performance (400-m; $r^2=0.56$; Rodríguez, Keskiner, Keskiner, & Malvela, 2003); however, it has not been tested for regional-level swimmers.

Managing the stroking parameters is a key performance aspect that coaches should consider when designing training(Cortesi, Di Michele, Fantozzi, Bartolomei, & Gatta, 2021). Recent studies have widely adopted 200-m maximal swims for competitive swimmers (Figueiredo et al., 2011) due to its average duration (~2 min to 2.5 min on average), sufficient to elicit $\dot{V}O_{2max}$ in most cases (Rossiter, Kowalchuk & Whipp, 2006). In a 200-m front crawl race, the inter-lap stroke rate (SR) develops a U-shaped manner with a smooth increase at the end of the effort to compensate for the decrease in stroke length (SL) because of the augmented effort when attempting to maintain a constant speed(Figueiredo, Sanders, Gorski, Vilas-Boas, & Fernandes, 2013; Koga et al., 2024). Thus, swimmers adjust their speedby adapting their SR and SL since an almost even pace is optimal for 200-m swimming performance across all strokes (Figueiredo et al., 2011; Figueiredo et al., 2013; Franken, Ludwing, Cardoso, Silveira, & Castro, 2016). Biomechanical and physiological factors have strongly influenced the middle-distance event performance and should be analyzed in conditions like those of free swimming in a pool (Jürimäe et al., 2007).

Therefore, different parameters that might affect swimming performance should be further studied considering both physiological and biomechanical aspects (Jürimäe et al., 2007). This study aimed to assess the $\dot{V}O_{2peak}$ through the post-exercise method and general stroke kinematics during a 200-m performance by comparing the swimmers' mechanics comparing the laps and correlating the $\dot{V}O_{2peak}$ and OUES with 200-m time. We hypothesized that swimmers would change their stroke frequency, length, stroke index, and velocity, showing fatigue effects; in addition, a strong association among the $\dot{V}O_{2peak}$, OUES, and 200-m front crawl performance would be observed. Our study might contribute to highlighting evidence for regional-level swimmers concerning training adjustments and performance improvement.

Material and methods

Fourteen regional-level front crawl swimmers volunteered to participate in this study. The participants had the following individual and mean (±SD) values for the subjects' main physical and performance features: age 16.14 ± 2.68 years, height 1.65 ± 0.08 m, and body mass 58.17 ± 7.76 kg. The swimmers had at least 4 years of competitive experience and trained normally during the data collection (5 ± 1 day) period with 4,000 ± 300 m of volume per session. This study was conducted in the first macrocycle (6 weeks) of the training season. All swimmers were in the base training period during the protocol. All the procedures described following were approved by the institutional ethics committee, according to the Helsinki Declaration for human experiments. All participants were fully informed on the procedures and demands of the study and signed a written informed consent form approved by the institutional ethics committee, according to the Brazilian Council of Ethics in research with human subjects.

The test sessions took place in a 25-m indoor swimming pool with a water temperature of 27.5°C. After a standard competition warm-up (Chaverri et al., 2016), all subjects rested outside the water while the equipment was set up and calibrated for the experiments. The swimmers performed an all-out 200-m front crawl with a block start and with no companions in the same lane or either one next to it to determine VO_{2peak}. Time was manually recorded to the nearest 0.01 s by three experienced timers, and the median values were used for analysis. The swimmers were encouraged to swim with their best effort.

The swimmers performed the 200-m effort without the respiratory equipment (i.e. completely unrestricted swimming; cf.Rodríguez et al., 2017). The VO_2 was collected using a portable metabolic system (VO2000, The Med Graphics, Minnesota, USA), with a patented flowmeter and a proportional sampling valve and a 3-breath average to measure $\dot{V}O_2$, carbonic gas volume (VCO_2), ventilatory expiration (VE), and $\dot{V}O_2$ efficiency slope (OUES). For a more detailed, see Crouter, Antezak, Hudak, DellaValle, & Haas, 2006; Jürimäe et al., 2007; Han et al., 2021.

The VO2000 was calibrated according to the manufacturer's instructions before testing, by performing an auto-calibration routine on a software using a proprietary room air calibration of the oxygen and carbon dioxide analyzers, as well as an auto-calibration procedure for the pneumotach. The software program used for the VO2000 does not allow for a two-point calibration using known gas volumes or manual calibration of the pneumotach with a calibration syringe.

The oronasal mask (VO2000, The Med Graphics, Minnesota, USA) was firmly applied immediately after the swim with care to avoid leakage and to minimize the time before the first respiratory data with the subject resting in the water in an upright position immersed to the mid-sternum(Wahrlich, Anjos, Going, & Lohman, 2006; Chaverri et al., 2016). The swimmers were instructed about the proper technique before the swims and the interchangeability of the oronasal mask used was previously established (Rodríguez et al., 2017). The $\dot{V}O_{2peak}$ was measured as averaged values measured within the first 20 s of recovery (Chaverri et al., 2016).

The stroke was obtained based on parameters from manual timekeeping of the front crawl. The time values were collected in the 25 m laps that preceded partials of 50 m (L1), 100 m (L2), 150 m (L3), and 200 m (L4). The manual timekeeping involved marking a between 10 and 20 m in the pool to minimize the effects of propulsion against the edge. Thus, the time of 10 m in pure swimming and the time for executing three full stroke cycles were timed by two experienced evaluators using timers (Technos, model 100 lap memory, Switzerland). All sections had a 0.01 s resolution. In case none of the timekeepers obtained the same time in a tenth of a second, the intermediate value (difference greater than 0.2 s) or the highest value (difference of 0.1) was used. The swimmer's head passing by the demarcated area markers of 10 m was always used as a reference (Franken et al., 2016).

The swimming speed was obtained by dividing the distance (10 m) and the time (s) needed to go through it. The stroke rate was determined based on the ratio of the three-stroke cycles throughout 10 m of the pool and the time to perform it. The stroke length was obtained from the ratio between the mean swimming speed (SS) obtained in the range of 10 m and SR (Franken et al., 2016).

The descriptive data are expressed as mean and SD calculated after the normality of distribution and homogeneity of variance, both checked and confirmed with the Shapiro-Wilk and Levene tests. However, non-parametric inferential tests were assumed due to the sample size. The relationship between the physiological variables ($\dot{V}O_{2peak}$, RQ, and OUES) and 200 m front crawl time was assessed through Spearman's coefficient of determination (rho). The magnitude of the correlation coefficients was assumed as .90 to 1.00 (very high), 0.70 to 0.90 (high), 0.50 to 0.70 (moderate), 0.30 to 0.50 (low), and 0.00 to 0.30 (negligible; c.f. Hinkle, Wiersma, & Jurs, 2003). ANOVA was applied for repeated measures and a Mauchly test verified the data sphericity. The main effects were checked by a posthoc Bonferroni to compare values of SR, SL, SS, and SI among laps L1, L2, L3, and L4 of 200 m. The effect size (eta^2) was also calculated. The level of significance was set at $p < 0.05$ and all statistical analyses were perfomed on SPSS 23.0 for Windows.

Results and discussion

Table 1 presents the anthropometric characteristics (age, body mass, and height), performance in the 200-m front crawl, and $\dot{V}O_{2peak}$ of the group of swimmers.

Table 1. Sample characterization of the group of swimmers evaluated; n = 14.

	Age (years old)	Body mass (kg)	Height (m)	Performance 200-m (s)	$\dot{V}O_{2peak}$ (ml⊠kg⊠min^{-1})
Average	16.14	58.17	1.65	141.58	38.59
SD	2.68	7.76	0.08	12.39	10.15
Minimum	13.08	45.45	1.45	122.51	15.56
Maximum	23.14	72.88	1.80	162.93	54.12

The group of swimmers (n = 14) reached a mean velocity of 1.42 ± 0.12 m·s^{-1} in the 200-m front crawl performance. Table 2 presents the values of SR, SL, SS, and SI obtained from 25-m sections before laps of 50, 100, 150, and 200-m (L1, L2, L3, and L4, respectively). A decrease in SR values was found only between L1 and L3 ($F_{3.39}$ = 4.089; $p <$ 0.05; η^2 = 0.239). The laps of the 200-m performance had similar SL values ($F_{3.11}$ = 2.076; p = 0.162; η^2 = 0.362). Furthermore, lower SS values were found only between L1 and L2, L3 and L4, and L2 and L4 ($F_{3.39}$ = 22.279; $p <$ 0.001; η^2 = 0.632). Lower SI values were found only between L1 and L3 and L4 ($F_{1.13}$ = 9.760; p < 0.001; η^2 = 0.429).

Table 3 shows the correlation matrix between the time values in the 200-m swimming front crawl performance and the $\dot{V}O_{2peak}$, respiratory quotient (RQ), and OUES for the group of swimmers (n = 14).

According to Table 3, a negative and significant correlation was found only between $\dot{V}O_{2peak}$ and time in the performance of the 200-m front crawl (rho = -0.653; p = 0.011), thus indicating that the higher the $\dot{V}O_{2peak}$ values, the lower the values of the time variable in the performance of 200-m front crawl swimming.

Table 2. Stroke rate (SR), stroke length (SL), mean swimming speed (SS), and stroke index (SI) in laps L1 (25-50 m), L2 (75-100 m), L3 (125-150 m), and L4 (175-200 m) of 200 m front crawl; n = 14.

	L1	L2	L3	L4
SR (ciclos·min^{-1})	44.72 ± 9.98	43.15 ± 9.38	40.82 ± 8.61*	42.34 ± 8.88
	(19.42; 57.69)	(19.05; 63.16)	(19.54; 56.07)	(19.67; 57.69)
SL (m)	2.06 ± 0.59	2.00 ± 0.63	2.00 ± 0.53	1.90 ± 0.43
	(1.57; 3.84)	(1.28; 3.98)	(1.51; 3.62)	(1.33; 3.13)
SS (m·s^{-1})	1.45 ± 0.10	1.35 ± 0.11$^{\Pi}$	1.30 ± 0.11	1.28 ± 0.13$^{\Omega}$
	(1.24; 1.63)	(1.12; 1.55)	(1.04; 1.50)	(1.03; 1.47)
SI (m^2·s^{-1}·cycles^{-1})	2.97 ± 0.71	2.71 ± 0.84	2.60 ± 0.65*	2.43 ± 0.50$^{\Omega}$
	(2.12; 4.77)	(1.61; 5.03)	(1.58; 4.26)	(1.63; 3.22)

*indicates difference from L1 to L3 ($p<0.05$); Ω indicates differences from L1 to L2, L3 and L4 ($p<0.05$); Π indicates difference between L2 and L4 sections ($p<0.05$).

Table 3. Spearman's test correlation matrix values (rho) between time in 200 m swimming front crawl performance (200 m performance) and the peak oxygen uptake (VO_{2peak}), the respiratory quotient (RQ), and the oxygen uptake efficiency slope (OUES) for the group of swimmers; n = 14.

Variables	Means and Standard Deviations	200 m performance (rho; p)
VO_{2peak} (ml·kg·min^{-1})	38.59 ± 10.15	rho = -0,653*; p = 0,011
RQ	1.44 ± 0.11	rho = -0,272; p = 0,346
OUES	33.21 ± 5.54	rho = -0,175; p = 0,549
200 m performance (s)	141.58 ± 12.39	-

The VO_{2peak} during a 200-m unrestricted front crawl effort allows testing swimmers under conditions very similar to the competitive situation without altering in any way the swimming mechanics(Chaverri et al., 2016; Rodríguez et al., 2017). This study aimed to analyze the effects of the 200 m all-out front crawl effort laps in the general stroke mechanics and verify the association among VO_{2peak}, OUES, and 200-m time. Our main findings partially confirm our hypothesis, as follows: (i) the 1st lap had a higher SR than the the 3rd lap; the 1st lap had a higher SS than the subsequent laps; the 2nd lap was greater than the 4th lap ($p < 0.05$); the 1st lap had a higher SI than the subsequent laps, and (ii) moderate and inverse coefficient of correlation appeared between the VO_{2peak} and 200-m time and the OUES does not seem to relate to performance.

As expected,the stroke mechanics management changed along the 200-m effort (Figueiredo et al., 2013; Cortesi et al., 2021). The SR behavior corroborated previous results indicating a U-shape, although an increase in the last lap was not significant (Figueiredo et al., 2013). Despite SS and SI decreasing during the effort, the SL did not change. The most commonly used pacing strategies for elite swimmers' 200-m front crawl are parabolic shaped, with a fast followed by an evenly paced midsection and a fast end sprint(Figueiredo et al., 2011; Cortesi et al., 2021).

Based on our results, swimmers can maintain certain SR along a swimming test but are usually unable to maintain SL values due to potential fatigue. Similar SS behavior was found for the 200 m front crawl among the 16 finalists of the 200 m freestyle race at the French National Championship, including four high-competitive level and six competitive Portuguese swimmers (Figueiredo, Vilas-Boas, Seifert, Chollet, & Fernandes, 2010). The study indicated that the SS decreased between the L1 and the L4 of the race. Such lower SL would be related to the inability to maintain the swimming technique, which would allow a larger distance traveled in each stroke cycle. In contrast, an attempt to eliminate the effect of the reduced SL on the SS values would be to increase SR. These results might be explained by the development of localized muscle fatigue(Zamparo, Turri, Peterson, & Poli, 2014), resulting in a lesser ability to generate power (Toussaint & Truijens, 2005).

Since Montpetit, Léger, Lavoie, and Cazorla (1981), the validity of VO_{2max} conventional test assessment has been questioned due to several reasons (e.g. mechanical changes), including reagrding the measurements of VO_{2peak} during maximal free crawl swimming using post-exercise VO_2 assessment. Previous studies indicated a higher mean speed at which the VO_{2peak} was reached in swimming without equipment (~13 to 16% and 5 to 6% in 100 m and 400-m front crawl) than during the conventional test with mouthpiece and tubing(Rodríguez et al., 2017; Montpetit et al., 1981). The use of swimming snorkels might alter swimming technique mechanics (e.g. reducing body rolling) and breathing patterns, thus unabling to perform diving starts or flip turns (Barbosa et al., 2010b). Herein, swimmers obtained absolute VO_{2peak} values below those found in the literature involving elite swimmers (absolute values ~3.5 assessed post-exercise; e.g.Chaverri et al., 2016), however close to the prepubertal swimmers (Jürimäe et al., 2007). The moderate association between VO_{2peak} and 200-m front crawl performance was expected since competitive swimming performance depends on the swimmer's maximal metabolic power (aerobic energy sources; Rodríguez et al., 2017).

Post-exercise VO_2 measurements allow swimmers to exercise without being hindered by the respiratory equipment and exploit their maximal potential (Montpetit et al., 1981; Chaverri et al., 2016;Rodríguez et al., 2017). Despite our important findings, some limitations might be pointed out, such as the absence of a wider range of metabolic variables assessed and a more detailed kinematic analysis.

Conclusion

Assessing cardiorespiratory fitness in cases where the swimming technique has to be maintained and race speed is to be reached requires carrying outall-out, filly unrestricted swimming for the swimmers to perform without being hindered by the respiratory equipment. Our results allow us to conclude that (I) SR changed between the 1st and 3rd laps and SS and the 1st lap had a higher SIthan the subsequent laps; in addition, (II) a moderate and inverse coefficient of correlation was found between the absolute VO_{2peak} and 200-m time. Understanding the physiological and biomechanical changes in 200-m all-out front crawl in regional-level swimmers based on the post-effort VO_2 assessment method might improve the application of appropriate training stimuli.

Acknowledgments

This work was supported by the Amazonas Research Support Foundation for Research of the State of Amazonas (FAPEAM), Infrastructure Program for Young Researchers – First Project Program PPP, no. 004/2017 under the grant (062.01554/2018). This study was also supported by the National Council for Scientific and Technological Development (CNPq) for funding the Scientific Initiation Scholarship (PIB-S/0055/2022). Funders had no role in the study design, data collection and analysis, decision to publish, or manuscript preparation.

References

Barbosa, T., Silva, A. J., Reis, A. M., Costa, M., Garrido, N., Policarpo, F., & Reis, V. M. (2010a). Kinematical changes in swimming front crawl and breaststroke with the Aqua Trainer snorkel. *European Journal of Applied Physiology,109*(6), 1155-1162. DOI: https://doi.org/10.1007/s00421-010-1459-x

Barbosa, T. M., Bragada, J. A., Reis, V. M., Marinho, D. A., Carvalho, C., & Silva, A. J. (2010b). 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. DOI: https://doi.org/10.1016/j.jsams.2009.01.003

Chaverri, D., Schuller, T., Iglesias, X., Hoffman, U., & Rodríguez, F. (2016). A new model for estimating peak oxygen uptake based on postexercise measurements. *International Journal of Sports Physiology and Performance, 11*(4), 419-424. DOI: https://doi.org/10.1123/ijspp.2015-0227

Cortesi, M., Di Michele, R., Fantozzi, S., Bartolomei, S., & Gatta, G. (2021). Arm-stroke descriptor variability during 200-m front crawl swimming. *Sensors, 21*(2), 324. DOI: https://doi.org/10.3390/s21020324

Crouter, S. E., Antczak, A., Hudak, J. R., DellaValle, D. M., & Haas, J. D. (2006). Accuracy and reliability of the ParvoMecics TrueOne 2400 and MedGraphics VO2000 metabolic systems. *European Journal of Applied Physiology, 98*(2), 139-151. DOI: https://doi.org/10.1007/s00421-006-0255-0

De Jesus, K., Sousa, A., De Jesus, K., Ribeiro, J., Machado, L. J., Rodriguez, F.... Fernandes, R. J. (2015). The effects of intensity on VO_2 kinetics during incremental free swimming. *Applied Physiology Nutrition and Metabolism, 40*(9), 918-23. DOI: https://doi.org/10.1139/apnm-2015-0029

Fernandes, R. J, Cardoso, C. S., Soares, S. M., Ascensão, A., Colaço, P. J., & Vilas-Boas, J. P. (2003). Time limit and VO2 slow component at intensities corresponding to VO2max in swimmers. *International Journal of Sports Medicine, 24*(8), 576-581. DOI: https://doi.org/10.1055/s-2003-43274

Fernandes, R. J., de Jesus, K., Baldari, C., de Jesus, K., Sousa, A. C., Vilas-Boas, J. P., & Guidetti, L. (2012). Different VO2max time-averaging intervals in swimming. *International Journal of Sports Medicine, 33*(12), 1010–1015. DOI: https://doi.org/10.1055/s-0032-1316362

Figueiredo, P., Sanders, R., Gorski, T., Vilas-Boas, J. P., & Fernandes, R. J. (2013). Kinematic and electromyographic changes during 200 m front crawl at race pace. *International Journal of Sports Medicine, 34*(1), 49–55. DOI: https://doi.org/10.1055/s-0032-1321889

Figueiredo, P., Vilas-Boas, J. P., Seifert, L., Chollet, D., & Fernandes, R. J. (2010). Inter-Limb Coordinative Structure in a 200 m Front Crawl Event. *The Open Sports Sciences Journal, 3*(1), 25-27. DOI: https://doi.org/10.2174/1875399X01003010025

Figueiredo, P., Zamparo, P., Sousa, A., Vilas-Boas, J. P., & Fernandes, R. J. (2011). An energy balance of the 200 m front crawl race. *European Journal of Applied Physiology, 111*, 767-77. DOI: https://doi.org/10.1007/s00421-010-1696-z

Franken, M., Ludwig, R. F., Cardoso, T. P., Silveira, R. P., & Castro F. A. S. (2016). Performance in 200 m front crawl: coordination index, propulsive time and stroke parameters. *Revista Brasileira Cineantropometria e Desempenho Humano, 18*(3), 311-321. DOI: https://doi.org/10.5007/1980-0037.2016v18n3p311

Han, S-C., Fu, T-C., Hsu, C-C., Huang, S-C., Lin, H-Y., & Wang J-S. (2021). The validation of oxygen uptake efficiency slope in patients with stroke. *Medicine, 100*(42). DOI: http://dx.doi.org/10.1097/MD.0000000000027384

Hinkle, D. E., Wiersma, W., & Jurs S. G. (2003). *Applied statistics for the behavioral sciences.* 5th ed. Boston: Houghton Mifflin.

Holmer, I. (1972). Oxygen uptake during swimming in man. *Journal of Applied Physiology, 33*(4), 502-509. DOI: https://doi.org/10.1152/jappl.1972.33.4.502

Jürimäe, J., Haljaste, K., Cicchella, A., Latt, E., Purge, P., Leppik, A., & Jürimäe, T. (2007). Analysis of swimming performance from physical, physiological and biomechanical parameters in young swimmers. *Pediatric Exercise Science, 19*(1), 70-81. DOI: http://dx.doi.org/10.1123/pes.19.1.70

Koga, D., Gonjo, T., Kawai, E., Tsunokawa, T., Sakai, S., Sengoku, Y,....Takagi, H. (2024). Effects of exceeding stroke frequency of maximal effort on hand kinematics and hand propulsive force in front crawl. *Sports Biomechanics, 23*(1), 15-27. DOI: https://doi.org/10.1080/14763141.2020.1814852

Leger, L. A, Seliger, V., & Brassard, L. (1980). Backward extrapolation of VO_2max values from the O_2 recovery curve. *Medicine & Science in Sports Exercise, 12*(1), 24-27.

Monteiro, A. S., Carvalho, D. D., Azevedo, R., Vilas-Boas, J. P., Zacca. R., & Fernandes, R. J. (2020). Post-swim oxygen consumption: assessment methodologies and kinetics analysis. *Physiolpgical Measurement,41*(10), 105005. DOI: https://doi.org/10.1088/1361-6579/abb143

Montpetit, R. R., Léger, L. A., Lavoie, J-M., & Cazorla, G. (1981). VO_{2peak} during free swimming using the backward extrapolation of the O_2 recovery curve. *European Journal of Applied Physiology and Occupational Physiology, 47*(4), 385-391. DOI: https://doi.org/10.1007/bf02332966

Rodríguez, F. A., Chaverri, D., Iglesias, X., Schuller, T., & Hoffmann U. (2017). Validity of Postexercise Measurements to Estimate Peak VO_2 in 200-m and 400-m Maximal Swims. *International Journal of Sports Medicine, 38*(06), 426-438. DOI: https://doi.org/10.1055/s-0042-123707

Rodríguez, F. A., Keskinen, K. L., Keskinen, O. P., & Malvela, M. (2003). Oxygen uptake kinetics during free swimming: a pilot study. *Biomechanics and Medicine in Swimming IX.* 379-384.

Rossiter, H. B., Kowalchuk, J. M., & Whipp, B. J. (2006). A test to establish maximum O2 uptake despite no plateau in the O2 uptake response to ramp incremental exercise. *Journal Applied Physiology, 100*(3), 764-770. DOI: http://dx.doi.org/10.1152/japplphysiol.00932.2005

Toussaint, H. M., & Truijens, M. J. (2005). Biomechanical aspects of peak performance in human swimming. *Animal Biology, 55*(1), 17-40. DOI: http://dx.doi.org/10.1163/1570756053276907

Wahrlich, V., Anjos, L. A., Going, S. B., & Lohman T. G. (2006). Validation of the VO2000 calorimeter for measuring resting metabolic rate. *Clinical Nutrition, 25*(4), 687–692. DOI: https://doi.org/10.1016/j.clnu.2006.01.002

Zamparo, P., Turri, E., Peterson, S. R., & Poli, A. (2014). The interplay between arms-only propelling efficiency, power output and speed in master swimmers. *European Journal of Applied Physiology, 114*(6), 1259-1268. DOI: https://doi.org/10.1007/s00421-014-2860-7