The relationship between tethered swimming, anaerobic critical velocity, dry-land strength, and swimming performance

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Abstract

This study aimed to 1) examine the associations between two swim-specific measures of anaerobic performance and dry-land strength-based variables; 2) study the association between the aforementioned variables with swimming performance and its kinematics; 3) analyse sex-induced differences. Twenty-three regional-national swimmers performed five countermovement-jumps and pull-ups, 50-m front crawl, two 30-s tethered-swimming tests at 0 and 1.124 $m \cdot s^{-1}$ water flow speed. Moreover, 10, 15, 20, and 25-m maximal front crawl were performed to determine anaerobic critical velocity (AnCV). The AnCV was positively correlated with tethered swimming variables in both conditions and dry-land based variables in both males and females ($p<0.05$). Tethered-swimming variables in both conditions were correlated with pull-ups' average propulsive force in males ($p<0.05$). 50-m swimming performance was positively associated with AnCV, tethered-swimming variables, countermovement-jump height, and pull-ups' average propulsive force for both sexes ($p<0.05$). Stroke rate (SR) was positively associated with AnCV in males and females ($p<0.05$). Stroke length was correlated with tethered-swimming variables in males ($p<0.05$). Except for SR, male presented higher values than female swimmers ($p<0.05$). Depending on the conditions of their training environment (equipment, time and/or the number of lanes available) coaches might use the AnCV and tethered-swimming variables as interchangeable tools for evaluating anaerobic performance.

Keywords: kinematics, sprint, power, assessment, evaluation, performance analysis.

Introduction

The accuracy and reliability in the assessment of the components that influence performance are crucial in the improvement of swimmers' results (Smith, Norris, & Hogg, 2002). Specifically, the water environment complicates the direct measurement of the components that affect performance, resulting in most cases in land-based measures. Notwithstanding its reliability and efficacy in determining adaptations after training, land-based measures do not meet the criterion of specificity and neglect the swimming technique (Dalamitros, Manou, & Pelarigo, 2014). Indeed, muscular force production while stroking (Keskinen, Tilli, & Komi, 1989), swimming technique (Barbosa et al., 2010), and aerobic/anaerobic energy production (Zamparo, Cortesi, & Gatta, 2020) are determinants in competitive swimming and therefore, should be assessed in the water.

As part of their training plan, swimmers perform several sessions per week of dry-land resistance training to improve the muscular force production in the water (Crowley, Harrison, & Lyons, 2018). The performance enhancements prompted by the strength training has been mostly studied by analysing the associations between the changes in strength with swimming performance (Crowley, Harrison, & Lyons, 2017; Muniz-Pardos et al., 2019). However, despite the strength gains reported in some studies, these improvements did not elicit any changes in free swimming performance (Manning, Dooly-Manning, Terrell, & Salas, 1986; Song, Park, & Jung, 2009), possibly, because of the non-swim-specific nature of the dry-land exercises (Crowley et al., 2017). Hence, to understand whether the changes in muscular strength would evoke changes in in-water swimming strength, tethered swimming has been widely used (Sadowski, Mastalerz, Gromisz, & Niźnikowski, 2012). Certainly, some dry-land exercises such as bench press or lat pull-down have been correlated with tethered swimming variables (Crowe, Babington, Tanner, & Stager, 1999; Loturco et al., 2016; Morouço et al., 2011). However, among the exercises studied, there is no related information with the pull-up, even though it is widely used by swimming strength and conditioning coaches, and has been stated as one of the best predictors of swimming speed (Crowley et al., 2018; Perez-Olea, Valenzuela, Aponte, & Izquierdo, 2018).

As for tethered swimming, this is a valid and reliable tool in swimming assessment, with muscular and physiological responses similar to free swimming, and which can be used to assess not only force production, but also anaerobic performance (Kjendlie & Thorsvald, 2006; Morouço, Marinho, Keskinen, Badillo, & Marques, 2014; Nagle Zera et al., 2021; Papoti et al., 2013). Indeed, the force parameters obtained in tethered swimming have been correlated with sprint swimming performance (Morouço et al., 2014; Ruiz-Navarro, Morouço, & Arellano, 2020; Santos, Bento, Pereira, & Rodacki, 2014), and anaerobic land-based tests (Amaro, Morouço, Marques, Fernandes, & Marinho, 2017; Nagle Zera et al., 2021). Nevertheless, most of the studies have been only conducted with male swimmers, and the sex-induced differences in tethered swimming parameters are unknown (Amaro et al., 2017).

Based on the concept of critical velocity, Fernandes et al., (2008) proposed the anaerobic critical velocity (AnCV). Expressed by the slope of the regression line between different short distances trials performed at maximum speed and the corresponding times, the AnCV is frequently used in the assessment of the anaerobic performance (Marinho, Barbosa, Silva, & Neiva, 2012). The shorter the testing distances used in AnCV evaluation, the stronger the relationship with sprint swimming performance (Fernandes, Aleixo, Soares, & Vilas-Boas, 2008). Among the different distances used in AnCV calculation, the 10, 15, 20, and 25 m have been well correlated with the speed in 50, 100, and 200 m in the four swimming strokes (Marinho et al., 2011; Marinho et al., 2012); i.e., the swimming distances with the highest anaerobic contribution preponderance (Troup & Trappe, 1994). In any case, the AnCV test has not been yet compared with other anaerobic tests, such as tethered swimming test.

In fact, knowing other tools that might be used interchangeably would be valuable for training monitoring Due to the cost of the equipment or the time and space required to perform the tethered swimming tests, some coaches might not be able to perform it, being unable to monitor some determinants of swimming performance such as the muscular force production while stroking or the anaerobic energy production (Keskinen et al., 1989; Zamparo et al., 2020), during their assessment routines. Therefore, in light of the above, the purpose of the current study was three-fold 1) to examine the associations between two swim-specific measures of anaerobic performance and dry-land strength-based variables; 2) to study the association between the aforementioned variables with swimming performance and its kinematic variables; and 3) to analyse the possible sex-induced differences. It was hypothesized that the two swim-specific measures of anaerobic performance would be correlated, showing high association with swimming performance. On the other hand, it was expected that male swimmers would present higher values than female swimmers in all the variables assessed.

Materials and Methods

Experimental approach to the problem

A cross-sectional study was conducted with a two-days test not separated by more than 48h to eliminate any residual fatigue effect among the tests. Participants were familiarized with the performance measurements prior to testing. Moreover, to improve the reliability of the measurements, participants were asked to refrain from intense exercise, alcohol, caffeine, or any stimulant drink during the test and on previous days.

The evaluation protocol was developed in a 25 m swimming pool (25 x 16.5 m) (water temperature 27.4 ºC, air temperature = 28.9ºC, and humidity 54%). Tethered forces were tested in a swimming flume (Endless Pool Elite Techno Jet Swim 7.5; HP, Aston PA) with predefined speed range and with flow speed being measured at 0.30 m depth using an FP101 flow probe (Global Water, Gold River, CA20)(Gay, López-Contreras, Fernandes, & Arellano, 2020) (water temperature 26.2ºC, air temperature = 29.1ºC, and humidity 46%).

Subjects

Twenty-three regional and national swimmers, 14 males (age: 17.47 ± 2.95 years old, height: 175.46 ± 7.85 cm, body mass: 67.59 ± 9.10 kg, and FINA points in 50 m freestyle: 410 ± 81, Level 5)(Ruiz-Navarro, López-Belmonte, Gay, Cuenca-Fernández, & Arellano, 2022) and nine females (age: 17.33 ± 2.40 years old, height: 166.87 ± 4.16 cm, mass: 60.82 ± 7.16 kg, and FINA points in 50 m freestyle: 515 ± 125, Level 4)(Ruiz-Navarro et al., 2022) volunteered to participated in the current study. Participants performed six training sessions per week under the supervision of the same coach with more than five years of regional or/and national experience. Before the beginning of the study, the protocol was fully explained to the participants and written consent to participate was requested (Parental consent for the swimmers under 18). The study was conducted according to the code of ethics of the World Medical Association (Declaration of Helsinki), and the protocol was approved by the university ethics committee (project code: 852).

Procedures

Countermovement jump assessment

Firstly, anthropometrics measurements were conducted using a stadiometer/scale (Seca 799, Hamburg, Germany) to obtain height and body mass. Before the strength measurements, swimmers conducted a standardized warm-up based on jogging, joint mobility, dynamic stretching, and three sub-maximal countermovement jump (CMJ) (Pérez-Castilla, Rojas, & García-Ramos, 2019). Five minutes after the end of the warm-up the participants were positioned in an upright stance with their feet shoulder-width apart with the arms on the hips, on the centre of a force plate sampling at 1,000 Hz (Dinascan/IBV, Biomechanics Institute of Valencia, Spain). Swimmers then performed five CMJs with one minute of rest in between. The participants were instructed to jump maximally and were encouraged in all the jumps. If the execution was not adequately performed (e.g., foot outside the plate during landing or horizontal displacement during the flight phase), an extra trial was conducted. From the five CMJs, the highest and lowest jumps were removed, and the mean height (CMJH) of the remaining jumps was calculated (Perez-Olea et al., 2018).

Pull-up assessment

After 10 minutes of rest, swimmers performed five pull-ups with one minute of rest in between. Swimmers were required to start the pull-ups hanging from a bar with pronated grip and with their elbows fully extended. The swimmers were required to perform as quickly as possible and only if the swimmers' chin reached the bar, the pull-up was considered as correct. Performance in the ascending phase of the pull-ups was recorded through an isoinertial dynamometer (T-Force Dynamic Measurement System, Ergotech, Murcia, Spain) attached to the subjects' hips through a harness. A researcher, inspected all pull-ups to assure that swimmers displaced vertically. If a horizontal movement was observed, an extra trial was conducted. The pull-ups which obtained the greatest and lowest mean velocity values were excluded, and the mean of the remaining was calculated (Perez-Olea et al., 2018). Average propulsive velocity, force, and power were obtained (PUv_{avg}, PUf_{avg}, and PUP_{avg}, respectively). Three of the female swimmers were unable to perform the pull-ups. Thus, analyses were conducted with the six that were capable.

Swimming performance assessment

Swimmers then performed a 1200 m standardized warm-up (300 m [100 m usual breathing, 100 m breathing every five strokes, 100 m usual breathing], 4 x 100 m [2 x {25 m kick + 25 m increased stroke length}] on 1:50, 8 x 50 m [2 x 50 m drill; 2 x 50 m building up speed, and 4 x {25 m race pace + 25 m easy}] on 1:00, and 100 m easy (Neiva et al., 2015). After ten minutes of rest, a 50 m all out trial was executed. The 50 m were recorded with a Sony FDR-AX53 at 50 Hz sampling rate (Sony electronics Inc., Tokyo, Japan) and the videos were analysed on an in-house customized software for race analysis in competitive swimming by one expert evaluator. Stroke rate (SR) was obtained by considering three upper limb cycles and dividing it by the time taken to complete the three cycles in every 25 m lap, Stroke length (SL) was obtained from the ratio between the velocity and SR, and stroke index (SI) was calculated by multiplying the swimming velocity by the SL (Gay et al., 2020). The Intra-class Correlation Coefficient (ICC) was computed to verify the absolute agreement between repeated measures, showing a very-high agreement ranging between 0.988 and 0.999.

Tethered swimming analysis

Thirty minutes after completion of the 50 m all out test, 30 s tethered swimming in two different conditions were performed: at zero speed and at 1.124 water flow speed ($m \cdot s^{-1}$) in a swimming flume. This speed was chosen since it was the maximum speed that allowed registering all the forces of the whole group of swimmers. A familiarization protocol with all the procedures was conducted previously. The test began with the participants swimming for 5 s at low intensity before the 30 s, to avoid inertial effect, adapted from Barbosa et al., (2013). The start and end of the 30 s were indicated with an auditory signal. A snorkel was used for tethered swimming to avoid interferences in force parameters caused by breathing (Pereira et al., 2013). There were 30 minutes of active rest between each trial. A steel cable was attached to the swimmer through a floating trapezoidal structure (which allows them to kick) and fixed to a load cell (RSCC S-Type; HBM, Darmstadt, Germany) leading to an angle of 10º with the water surface and recording at 1500Hz. Analog data were converted (celula 1.4; Remberg, Force Isoflex, Spain), registered, and exported (NIUSB600; National Instruments, Austin, TX) to a specific software (myoRESEARCH, Noraxon, USA), allowing to visualize the recordings in real time. The force-time curves were processed, with the angle correction, as recently stated (Baratto de Azevedo et al., 2021), using a fourth-order Butterworth low-pass digital filter, with a cut-off frequency of 4.5 Hz. From the force-time curves the following parameters were computed (Morouço, Marinho, Keskinen, Badillo, & Marques, 2014): average force (Favg), mean of force values recorded during the 30 s; maximum force (Fmax), highest value obtained from the individual force-time curve; average impulse (Iavg), quotient of the sum of the single-stroke impulse and the number of strokes performed during the 30 s tethered swim; and maximum impulse (Imax), highest value of the impulse of force in a single stroke.

Anaerobic critical velocity evaluation

On the second day, after the completion of the standardized warm-up swimmers performed the AnCV test, which consisted on all out front crawl swimming efforts to 10, 15, 20, and 25 m, with in-water starts and 30 minutes of passive rest between each trial. All the trials were recorded and analysed in the same in-house customized software for race analysis as the 50 m all out test. The AnCV was computed from the slope of the distance-time relationship (Marinho et al., 2011; Neiva, Fernandes, & Vilas-Boas, 2011). Given that the tests were conducted in a 25 m swimmers pool and to avoid the influence of the turn over the determination of the AnCV, those distances were chosen (Marinho et al., 2012).

Statistical analysis

The normality of all the variables was checked using Shapiro-wilk's test. Mean and standard deviation (SD) for descriptive analysis were obtained and reported for all studied variables. Pearson product-moment correlation coefficients (r) were used to verify the relationship between the swimming performance, kinematics variables, AnCV, and tethered swimming variables. Spearman's correlation coefficients were used for the variables that were not normally distributed. The threshold values denoting small, moderate, large, very large, and extremely large correlations were defined as 0.1, 0.3, 0.5, 0.7, and 0.9, respectively (Hopkins, Marshall, Batterham, & Hanin, 2009). Independent sample t-test was used to compare all the variables measured between male and female swimmers. Non-parametric independent sample t-test (Wilcoxon rank-sum test) was conducted in the non-normally distributed. As the results were identical, only parametric independent sample t-test data were reported (Alcantara et al., 2020). The effect sizes (d) of the obtained differences were calculated and categorized as small if $0 \leq |d| \leq 0.5$, medium if $0.5 < |d| \leq 0.8$, and large if $|d| > 0.8$ (Cohen, 1988). All statistical procedures were performed using SPSS 24.0 (IBM Chicago, IL, USA).

Results

In Table 1 are presented for both sexes the mean ± SD values for the swimming performance, 95% confident interval ([95%CI]), relative change, and effect sizes with [95%CI] (d) values for the swimming performance, kinematics variables, AnCV, tethered swimming variables, and the strength-based variables obtained on land. Table 2 reported the correlations between AnCV, tethered swimming variables, and the strength-based variables obtained on land for both male and female swimmers. Both males and females correlations between AnCV, tethered swimming variables, the strength-based variables obtained on land, and swimming performance and its kinematics are shown in Table 3.

(Please insert Table 1,2, and 3 near here)

Discussion

The aim of the current study was three-fold 1) to examine the associations between two swim-specific measures of anaerobic performance and dry-land strength-based variables; 2) to study the association between the aforementioned variables with swimming performance and its kinematic variables; and 3) to analyse the possible sex-induced differences. As hypothesized, the AnCV and tethered swimming were positively correlated ($p<0.05$). Tethered-swimming variables were correlated with pull-ups' average propulsive force in males in both conditions (zero speed and at 1.124 $m \cdot s^{-1}$ water flow speed in a swimming flume)($p<0.05$). Moreover, both AnCV and tethered swimming were positively associated with swimming performance ($p<0.05$). Finally, except for SL and PUf_{avg}, males showed higher values than females in all the variables assessed.

As it was hypothesized, AnCV and tethered swimming variables presented positive correlations between them, especially in male swimmers, since AnCV as well as tethered swimming variables have been previously stated as anaerobic performance indicators (Fernandes, R., Aleixo, I., Soares, S., & Vilas-Boas, 2008; Nagle Zera et al., 2021). Both were also correlated with the dry-land based variables (i.e., CMJH and PUf_{avg}). The higher correlation in males than in females between AnCV, tethered swimming variables, and dry-land base variables might be explained by the different contribution of arms and legs to force generation between sex (Morouço, Marinho, Izquierdo, Neiva, & Marques, 2015). The fact that CMJH presented better correlations with AnCV and swimming performance in females than males might indicate that females' arm propulsion was heterogeneous but the difference relied on the kicking action, whose propulsive role is higher as the swimming velocity decreases (i.e., females presented lower speed than males and therefore higher propulsion must be generated in females than in males) (Gatta, Cortesi, & Di Michele, 2012).

Swimming performance was correlated with AnCV, tethered swimming, and dry-land based variables. These results are in agreement with previous research (Loturco et al., 2016; Marinho et al., 2012; Perez-Olea et al., 2018), proving that the swimmers with higher anaerobic function are capable of developing higher amount of force in the water; thus, being the fastest. In this regard, despite previous studies investigated the isolated associations of AnCV (Marinho et al., 2012; Neiva et al., 2011), tethered forces (Morouço et al., 2014; Ruiz-Navarro et al., 2020; Vorontsov, Popov, Binevsky, & Dyrko, 2006), or land-based measures to swimming performance (Perez-Olea et al., 2018), the current investigation is one of the few studies that presents a comprehensive approach of these three determinants aspects.

Female swimmers also presented positive correlation between AnCV, tethered swimming, and dry-land base variables. The variable with the highest correlation with performance was CMJH (Table 3). This could be explained by several reasons: 1) The propulsive role of leg kicking is higher at lower velocities (Gatta et al., 2012), therefore, the female swimmers with the most powerful lower limbs could make a difference; 2) the tests were conducted in a 25 m swimming pool, were the start and turn have a big influence on the final outcome (Sánchez, Arellano, & Cuenca-Fernández, 2021). Moreover, the start and turn are highly correlated with CMJH (Hermosilla, Sanders, Gonz, Yustres, & Gonz, 2021; Thng, Pearson, & Keogh, 2019). Thus, females with superior jumping skills may be able to generate a greater impact on the final outcome. On the other hand, female swimmers presented worse correlation as the water flow speed increased. These results are contrary to male behaviour (Table 3) and previous work (Ruiz-Navarro et al., 2020; Vorontsov et al., 2006). Despite it was previously tested that all the swimmers could produce force at the water flow speed selected, it is possible that female swimmers struggled to keep the position in the swimming flume, focusing on trying not to be carried away by the water flow rather than to give their best effort.

From a kinematic perspective, swimming velocity is determined by SR and SL, and an increment or reduction of either of these two parameters has an impact on swimming velocity (Barbosa et al., 2010). Consequently, the positive correlation of the kinematic variables with tethered swimming variables in male swimmers, especially at 1.124 water flow speed ($m \cdot s^{-1}$), could be expected (Table 3). Swimmers with higher ability to apply the force would be able to increase the propulsion and therefore the distance covered per stroke (i.e., SL). By contrast, SR was not correlated with tethered force variables. Despite, SR is related to neuromuscular power and energy capacities (Wakayoshi, D'Acquisto, Cappaert, & Troup, 1995), an increase in neuromuscular mechanisms does not essentially represent an increase in the ability to generate propulsive force by the body, but rather an increase in the movements that occur against the water, which in a sense could result in a slippery effect on the stroke cycle. Therefore, increases in SR may not be in line with increases in propulsive force (Cuenca-Fernández et al., 2020). Both male and female presented significant correlations among CMJH and SR. The same result has been previously observed, but it was not discussed (Strzała & Tyka, 2009). Possibly the muscle coordination required during the jump had certain association with the kicking technique, which is known to affect SR (Yanai, 2003). Future studies are required to clarify this issue though.

As a valid indicator of swimming efficiency (Figueiredo, Zamparo, Sousa, Vilas-Boas, & Fernandes, 2011), SI was positively correlated with AnCV and tethered swimming variables in male swimmers. This means that swimmers with better ability to apply force in the water would be those with higher efficiency (i.e., SI). Since SI and swimming performance are associated (Sánchez & Arellano, 2002) it was expected that SI and AnCV were also associated. However, female swimmers only presented significant correlation among Iavg and SI, without correlation between Si and AnCV. In this regard, it is worth mentioning that the females' correlations were similar to males, but the lower sample may have precluded obtaining similar statistically significant relationships.

Males exhibited higher values of tethered swimming, dry-land based variables, and swimming performance than females. The differences between sex are well known (Janssen, Heymsfield, Wang, & Ross, 2000; Miller, Macdougall, Tarnopolsky, & Sale, 1993). And these results are in agreement with previous research (Arellano, Brown, Cappaert, & Nelson, 1994; Morouço et al., 2015; Nagle et al., 2017). However, contrary to previous research, female swimmers presented similar SL and lower SR than males. This could be due to lower SR values of females compared to previous work (Arellano et al., 1994; Gonjo & Olstad, 2021). Since SR and SL are inversely related (Craig & Pendergast, 1979), the fact that females' SR were that low, led to a higher SL than the presented in previously published studies. The different correlations observed among sex might explain that male swimmers relied more in their upper-body strength, while female swimmers relied more in their lower-body strength. Indeed, flutter kicking contribution is higher at lower speed (i.e., females had significant lower speed than males) (Gatta et al., 2012) and therefore its relative contribution to propulsion is higher in female than in male swimmers (Morouço et al., 2015).

In conclusion, the AnCV and tethered force parameters measured during 30 s tethered test are related, hence depending on the conditions of the training environment (i.e., equipment, time and/or the number of lanes available) both tests could be used by coaches as interchangeable tools for evaluating anaerobic performance. Moreover, despite the non-swim-specific nature of the CMJ and pull-up, both tests showed association with tethered swimming variables and performance, which suggests the use of both exercises as testing tools for assessing swimming performance and also as training exercises. Finally, coaches should be aware of the sex-induced difference when comparing males and females results, since males could present a higher reliance on the upper body muscle system compared to females.

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TABLES CAPTIONS

Table 1. The mean ± SD values for the swimming performance, 95% confident interval ([95%CI]), relative change (Δ%), and effect sizes (d) with [95%CI] values for the swimming performance, kinematics variables, anaerobic critical velocity, tethered swimming variables, and the strength-based variables obtained on land.

Table 2. Relationship between anaerobic critical velocity, tethered swimming variables, and the strength-based variables obtained on land for both male and female swimmers.

Table 3. Relationship between anaerobic critical velocity, tethered swimming variables, the strength-based variables obtained on land, and swimming performance and its kinematics.

Table 1. The mean ± SD values for the swimming performance, 95% confident interval ([95%CI]), relative change (Δ%), and effect sizes (d) with [95%CI] values for the swimming performance, kinematics variables, anaerobic critical velocity, tethered swimming variables, and the strength-based variables obtained on land.

	Variable	Males	Females	[95%CI]; Δ%	Effect size (*d*) [95%CI]
	S50m ($m \cdot s^{-1}$)	1.77 ± 0.11	1.59 ± 0.11	[0.07, 0.29]; 10.16%	1.64 [0.75, 2.52]**
	SL (m)	1.87 ± 0.14	1.88 ± 0.17	[-0.15, 0.13]; -0.53%	0.07 [-0.95, 0.82]
	SR (Hz)	0.89 ± 0.07	0.78 ± 0.10	[0.02 , 0.19]; 12.35%	1.32 [0.87, 1.76]*
	SI ($m^2 \cdot s^{-1}$)	3.12 ± 0.34	2.77 ± 0.26	[0.08, 0.64]; 11.21%	1.13 [0.69, 1.57]*
	AnCV ($m \cdot s^{-1}$)	1.67 ± 0.10	1.50 ± 0.08	[0.08, 0.25]; 10,17%	1.83 [0.94, 2.72]**
Water flow speed 0 $m \cdot s^{-1}$	Favg (N)	93.96 ± 21.02	68.12 ± 9.22	[10.30 ,41.39]; 27.50%	1.48 [0.59, 2.37]**
	Fmax (N)	227.74 ± 37.53	165.29 ± 24.94	[32.86, 92.94]; 27.42%	1.89 [1.45, 2.34]***
	Iavg (N·s)	63.96 ± 12.77	49.06 ± 6.33	[5.32, 42.48]; 24.47%	1.40 [0.96, 1.85]**
	Imax (N·s)	88.37 ± 20.09	65.62 ± 9.06	[7.85, 27.65]; 25.74%	1.36 [0.47, 2.25]**
Water flow speed 1.124 $m \cdot s^{-1}$	Favg (N)	40.92 ± 11.78	18.99 ± 6.40	[14.02, 29.86]; 52.59%	2.18 [1.29, 3.07]***
	Fmax (N)	121.80 ± 34.87	56.04 ± 14.58	[43.73, 87.78]; 53.99%	2.31 [1.87, 2.76]***
	Iavg (N·s)	26.08 ± 6.62	16.23 ± 6.51	[4.00, 15.70]; 37.76%	1.50 [1.05, 1.94]**
	Imax (N·s)	50.60 ± 18.91	20.65 ± 7.84	[16.05, 43.85]; 59.18%	1.91 [1.03, 2.80]***
	CMJ_{JH} (m)	0.33 ± 0.06	0.24 ± 0.04	[0.04, 0.14]; 27.27%	1.69 [0.80, 2.58]**
	PUv_{avg} ($m \cdot s^{-1}$)	0.69 ± 0.17	0.44 ± 0.15	[0.07, 0.43]; 36.23%	1.54 [1.10, 1.99]**
	PUf_{avg} (N)	664.66 ± 88.20	582.26 ± 75.73	[-5.83, 170.63]; 12.39%	0.99 [0.54, 1.43]
	PUP_{avg} (W)	458.77 ± 121.99	255.65 ± 81.99	[86.79, 319.47]; 44.27%	1.89 [1.45, 2.33]**

Speed in 50 meters (S50m), stroke length, rate, and index (SL, SR, and SI), Anaerobic critical velocity (AnCV), average force (Favg), maximum force (Fmax), average impulse (Iavg), maximum impulse (Imax), countermovement jump height (CMJh), Pull-up mean propulsive velocity (PUv_{avg}), Pull-up mean propulsive force (PUf_{avg}), pull-up mean propulsive power (PUP_{avg}). * $p < 0.05$, ** $p < 0.01$, and *** $p < 0.001$.

Table 2. Relationship between anaerobic critical velocity, tethered swimming variables, and the strength-based variables obtained on land for both male and female swimmers.

			Water flow speed 0 $m \cdot s^{-1}$				Water flow speed 1.124 $m \cdot s^{-1}$			
		AnCV	Favg	Fmax	Iavg	Imax	Favg	Fmax	Iavg	Imax †
MALE	AnCV	-	0.367	**0.656****	0.384	0.091	**0.602***	**0.532***	**0.579***	0.345
	CMJH	**0.522***	0.003	0.164	-0.036	-0.212	0.216	0.127	0.097	0.194
	PUv_{avg}	**0.712****	0.062	0.369	0.001	-0.052	0.279	0.238	0.151	0.074
	PUf_{avg}	**0.479***	**0.747****	**0.742****	**0.820*****	**0.832*****	**0.690****	**0.719****	**0.753****	**0.714****
	PUP_{avg}	**0.846*****	0.404	**0.658****	0.374	0.323	**0.575***	**0.553***	**0.483***	0.258
FEMALE	AnCV	-	**0.592***	0.503	0.570	0.417	0.476	0.178	0.343	**0.624***
	CMJH §	**0.607***	0.214	0.385	**0.633***	0.171	0.325	0.274	-0.359	0.496
	PUv_{avg}	-0.010	-0.657	-0.509	-0.422	-0.574	**-0.745***	-0.409	-0.606	-0.349
	PUf_{avg}	**0.790***	**0.895****	**0.833***	0.620	0.577	0.534	0.492	-0.153	0.548
	PUP_{avg}	0.256	-0.127	-0.22	-0.21	-0.374	-0.548	-0.232	-0.646	-0.159

Anaerobic critical velocity (ANCV), countermovement jump height (CMJH), Pull-up average velocity (PUv_{avg}), Pull-up average force (PUf_{avg}), pull-up average power (PUP_{avg}), average force (Favg), maximum force (Fmax), average impulse (Iavg), maximum impulse (Imax). † Spearman correlation used only in male swimmers § spearman correlation used only in female swimmers. * $p < 0.05$, ** $p < 0.01$, and *** $p < 0.001$.

Table 3. Relationship between anaerobic critical velocity, tethered swimming variables, the strength-based variables obtained on land, and swimming performance and its kinematics.

			Water flow speed 0 m·s^{-1}				Water flow speed 1.124 m·s^{-1}							
		AnCV	Favg §	Fmax	Iavg	Imax	Favg	Fmax	Iavg	Imax †	CMJ$_{JH}$ §	PUv$_{avg}$	PUf$_{avg}$	PUP$_{avg}$
MALE	S50m	**0.956*** **	0.321	**0.724** **	0.431	0.061	**0.572***	**0.622** **	**0.578***	**0.495***	**0.555***	**0.706** **	**0.500***	**0.852*** **
	SL	0.150	0.311	**0.483***	**0.505***	0.399	0.322	**0.524***	**0.499***	**0.569***	-0.122	-0.067	**0.516***	0.167
	SR †	**0.642** **	-0.009	0.134	-0.048	-0.365	0.172	0.319	0.042	0.004	**0.570***	**0.658***	-0.313	0.505
	SI	**0.633***	0.370	**0.705***	**0.545***	0.259	**0.528***	**0.700** **	**0.651** **	**0.565***	0.196	0.337	**0.574***	**0.561***
FEMALE	S50m	**0.915*** **	0.293	**0.608***	**0.627***	0.367	0.538	0.333	-0.396	**0.726***	**0.979*** **	0.112	**0.914** **	0.422
	SL	0.289	-0.300	0.042	0.283	0.246	-0.350	0.03	0.453	-0.113	-0.265	-0.244	-0.408	-0.391
	SR	**0.622***	0.444	0.27	0.086	-0.005	0.532	0.133	-0.479	0.398	**0.588***	0.171	**0.710***	0.419
	SI	0.403	0.150	0.488	**0.751***	0.501	0.087	0.275	0.19	0.429	0.522	-0.203	0.159	-0.158

Speed in 50 meters (S50m), stroke length, rate, and index (SL, SR, and SI), Anaerobic critical velocity (ANCV), average force (Favg), maximum force (Fmax), average impulse (Iavg), maximum impulse (Imax), countermovement jump height (CMJh), Pull-up mean propulsive velocity (PUv$_{avg}$), Pull-up mean propulsive force (PUf$_{avg}$), pull-up mean propulsive power (PUP$_{avg}$). † Spearman correlation used only in male swimmers § spearman correlation used only in female swimmers. * $p < 0.05$, ** $p < 0.01$, and *** $p < 0.001$.