TETHERED SWIMMING UNDER DIFFERENT FLOW VELOCITIES IN A SWIMMING FLUME. ITS RELATIONSHIP WITH SWIMMING PERFORMANCE

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ABSTRACT

Purpose: This study was aimed 1) to compare the association between tethered swimming (TS) variables at zero velocity, 0,926 m/s, 1,124 m/s, 1,389 m/s water flow velocity and swimming velocity (SV) in 25m, 50m and 100m freestyle, 2) to obtain the most reliable parameter at zero velocity, 3) to study the association between intra-cyclic force variation (*df*) , intra-cyclic velocity variation (*dv*) and performance 4) to compare swimming variables between 30s TS and 25m, 50m and 100m free swimming. **Methods**: This was a cross-sectional study. Sixteen regionals swimmers performed 25m, 50m and 100m front crawl effort and 30s TS in 4 different conditions, at zero velocity, 0,926 m/s, 1,124 m/s, 1,389 m/s water flow velocity. Force was obtained using a load cell and instantaneous velocity was measured by a speedometer. The SV in free swimming and stroke rate in both TS and free swimming was analysed using ASPA (Automatic Swimming Performance Analysis). **Results**: All TS variables at 1,389 m/s water flow velocity were positive associated with 25m SV ($p<0,05$). Mean force and maximum impulse at zero velocity were significantly associated with 25m SV ($p<0,05$). There was association between *df* and *dv* ($p<0,05$), but not with performance ($p>0,05$). TS variables were not significantly different to 50m free swimming variables ($p>0,05$). **Conclusion**: Tethered swimming measured in a swimming flume with a high water flow velocity is a more accurate tool to associate with performance than TS at zero velocity. Average force and maximum impulse at zero velocity are both associated with short sprint performance. *Df* and *dv* were not associated with performance. 30 second TS effort correspond with 50m free swimming but not correspond with 25m and 100m free swimming ($p<0,05$).

KEY WORDS: Tether forces, strength, training, exercise testing.

RESUMEN

Objetivo: Nuestros objetivos fueron 1) comparar la asociación entre las variables obtenidas en nado atado (NA) a velocidad cero, 0,926 m/s, 1,124 m/s, 1,389 m/s de velocidad de flujo y la velocidad de nado en 25m, 50m y 100m libres , 2) obtener el parámetro más fiable a velocidad cero, 3) estudiar la asociación entre la variación de fuerza intra-ciclo (*df*), la variación de velocidad intra-ciclo (*dv*) y el rendimiento y 4) comparar las variables de nado entre 30 segundos de NA y 25m, 50m y 100m nado libre. **Método**: Se llevó a cabo un estudio cros seccional. Dieciséis nadadores regionales realizaron 25m,50m y 100m y 30 segundos de nado atado en 4 condiciones, a velocidad cero y a velocidades de flujo de 0,926 m/s, 1,124 m/s, 1,389 m/s. La fuerza se registró con una célula de carga y la velocidad instantánea se midió con un velocímetro. La velocidad de nado en nado libre y la frecuencia de ciclo en NA y nado libre se midieron usando ASPA (Automatic Swimming Performance Analysis). **Resultados**: Las variables de fuerza en nado atado a 1,389 m/s velocidad de flujo estuvieron positivamente asociadas con la velocidad en 25m ($p<0,05$). Fuerza media e impulso máximo a velocidad cero estuvieron asociadas con el rendimiento ($p<0,05$). Hubo asociación entre *df* y *dv* ($p<0,05$), pero no con el rendimiento ($p>0,05$). Las variables de NA no fueron significativamente diferentes de las de 50m libres ($p>0,05$). **Conclusión**: El nado atado medido en una piscina contracorriente con velocidad de flujo alta es una herramienta más precisa para asociar con el rendimiento que a velocidad cero. Fuerza media e impulso máximo a velocidad cero están asociados con el rendimiento en 25m. *Df* y *dv* no están asociados con el rendimiento. El esfuerzo de 30s NA corresponde con el de 50m libres pero no con el de 25m ni 100m ($p<0,05$).

PALABRAS CLAVE: Fuerzas de nado atado, fuerza, entrenamiento, evaluación del entrenamiento.

1. INTRODUCTION

Performance in competitive swimming is measured through the time spent in a given distance. Muscular force production while stroking (Keskinen, Tilli, & Komi, 1989) , swimming technique (Barbosa et al., 2010) and aerobic/ anaerobic energy production (Narita, Nakashima, & Takagi, 2017) are determinant in competitive swimming performance. In short distances the force exerted in water must be high to overcome the water resistance and drag (Dominguez-Castells, Izquierdo, & Arellano, 2013). For that reason, the assessment of the force exerted in swimming became really important (Morouço, Marinho, Keskinen, Badillo, & Marques, 2014). However, the aquatic environment complicates the direct measurement of force application during swimming performance (Akis & Orcan, 2004). To overcome that problem, tethered swimming (TS) has been proposed as a valid and reliable methodology (Akis & Orcan, 2004; Amaro, Marinho, Batalha, Marques, & Morouço, 2014; Kjendlie & Thorsvald, 2006). Nevertheless, Maglischo, Maglischo, Sharp, Zier, & Katz (1984) showed kinematical differences between free swimming and TS. Vorontsov, Popov, Binevsky, & Dyrko (2006) suggested that using TS in a swimming flume would be a situation closer to free swimming than TS at zero velocity. On the other hand, Morouço, Marinho, Keskinen, Badillo, & Marques (2014) did not find significant differences between physiological variables in 30s TS and 50 m free swimming.

Tethered swimming is a tool to measure the exerted forces in water, assessing individual force-times curves during the exercise (Amaro, Morouço, Marques, Fernandes, & Marinho, 2017). The most common parameters obtained though that curve in the literature are: average force (Morouço, Keskinen, Vilas-Boas, & Fernandes, 2011) , maximum force (Keskinen et al., 1989) , average and maximum impulse

(Morouço et al., 2014). However, there is no clear evidence suggesting which one is the most reliable variable, confirming that more studies are needed to better understanding this topic. Considering that propulsion occurs during the whole propulsive phase of the stroke cycle (Marinho et al., 2011; Schleihauf, 1979), the relation between force and time should be considered as follows (Morouço et al., 2014):

$$I = \int_{t_1}^{t_2} F \cdot dt, \tag{1}$$

Where I represents the impulse of force, and F is the applied force from time t_1 to t_2. Consequently, calculations of the impulse of force may be more accurate when analysing the tethered forces (Dopsaj, Matkovíc, & Zdravkovíc, 2000), as the impulse of force depends on the magnitude, duration and direction of the applied force. In addition measures combining force and speed may be more accurate and relate to performance (Knudson, 2009)

Recently, Morouço, Barbosa, Arellano, & Vilas-Boas (2017) proposed a new parameter related to tethered force; intra-cyclic force variation (*df*). This variable seems to be valid for evaluating the swimmer's ability to effectively apply force in the water and highly associated to performance. Another commonly accepted variable is the intra-cyclic velocity variations (*dv*), even though the relationship with performance is not clear yet (Vilas-Boas, Fernandes, & Barbosa, 2011). An inter group comparison between breaststrokers showed that better swimmers had higher values of *dv* (Leblanc, Seifert, Tourny-Chollet, & Chollet, 2007). However, Takagi, Sugimoto, Nishijima, & Wilson (2004) found opposite results, breaststrokers who reached semi-finals at the 9th world swimming championships had lower *dv* than those who were eliminated in the preliminaries.

It is necessary to clarify this controversy and get over the limitations. To the best of our knowledge, there is no evidence of previous studies that analyse the relationship between the tethered variables at different water flow velocities and performance in short distances. Thus the aim of this study were: 1) to compare the association between TS variables at zero velocity, 0,926 m/s, 1,124 m/s, 1,389 m/s water flow velocity and swimming velocity (SV) in 25m, 50m and 100m freestyle, 2) to obtain the most reliable parameter at zero velocity, 3) to study the association between *df*, *dv* and performance and 4) to compare swimming variables between 30s TS and 25m, 50m and 100m free swimming.

2. METHODS

2.1. Subjects

Sixteen regional male swimmers participated in the study (19,60±3,29 years of age, 176 ± 4,52cm in height, 70,71±9,48 kg of body mass, 58,24± 2,27 s of long course 100 m freestyle personal best, representing 76±5% of the World record). To be included, the swimmers were required to have at least 5 years of experience in competitive swimming. The protocol was fully explained to the participants before they provided written consent to participate in the study. 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 (see attached document at the annex).

2.2. Experimental design and general procedures

A cross-sectional study was used. Our intention was to obtain TS variables, free swimming variables, *df* and *dv* parameters. Swimming performance was tested in a 25m swimming pool (25m x 16,5m) (water temperature = 27º, humidity= 65%) and tethered forces were measured in an swimming flume (figure 1; Ruiz-Teba, 2015) (water temperature= 26º, humidity= 52%) both located at the Swimming pool building at the faculty of Sport Sciences, University of Granada. Swimmers were tested in two consecutive days in the same conditions. To improve the reliability of the measurements, subjects were asked to refrain from intense exercise the day before and the test days. Moreover, they were asked to abstain from caffeine, alcohol or any stimulant drink during those days. Test were performed in the same conditions and both were preceded by a standardised warm up, which consisted of 1000m of low to moderate intensity front crawl swimming (400-m swim, 100-m pull, 100-m kick, 4x50-

m at increasing speed, 200-m easy swim) (Morouço et al., 2017). Execution order was randomly assigned.

2.3. Force recordings

The TS test consisted of 30 s front crawl in 4 different conditions, at zero velocity and at 3 different velocities of the water flow: 0,926m/s, 1,124 m/s, 1,389 m/s. The participants were familiarized with tethered swimming. Moreover, they underwent with a familiarization with all the procedures. A belt was attached to the hip with a 2m steel cable. Force recordings were synchronized with 3 different video cameras, using a video switcher (Roland Corporation, Roland Pro A/V V-1HD, Osaka, Japan) (figure 2). Visual-auditory signal was used to determine the start and the end of the 30 seconds. Before that, the participants swam for 5 seconds at low intensity, in order to avoid inertial effect, adapted from Barbosa, de Souza Castro, Dopsaj, Cunha, & Júnior (2013). Swimmers used snorkel to avoid breathing effects on the force parameters. Their feet were set on a rope. The leg action was excluded to avoid interaction with the arms and to prevent the feet from touching the wire and interfering with the measurements (Dominguez-Castells et al., 2013). There was 15 min of active rest between each trial. After the trial rate of perceived scale (RPE) was asked to the swimmers (Borg, 1982).

Forces were measured using a load cell (HBM, RSCC S-Type, Darmstadt, Germany) connected to the swimmers, recording at 200hz, with a measurement capacity of 4905 N. Data were recorded, converted (Remberg, Force Isoflex, celula 1..4, Spain) and exported to the load cell software (acquisitions, Granada, Spain) through the USB (National instruments, NI USB 600, Austin, USA). Stroke rate were recorded and analysed using ASPA (Automatic Swimming Performance Analysis) (figure 3) (Ref.: IE_57161).

2.4. Performance test

The swimmers performed 25m, 50m and 100m front crawl. An underwater start was used. During the 25m a speedometer cable (lineal transducer, Heidenhain, D83301, Traunreu, Germany) was attached to swimmer´s hip through a belt (figure 4). Data were recorded, converted (Signal Frame MF020, Sportmetrics, Spain) and exported to the software (Signalframe an v.2.00). The encoder voltage was recorded at 200 Hz. Total time, mean velocity, partial time, partial mean time, stroke length and stroke rate were recorded using ASPA (Automatic Swimming Performance Analysis) (Ref.: IE_57161).

2.5. Data analysis

Force-time and velocity-time curves were smoothed using a fourth order Butterworth low pass digital filter, with a cut off frequency of 100 hz. The following parameters were estimated for each TS trial (figure 5) (Morouço et al., 2014):

a) Maximum force (Fmax): highest value obtained from the individual force-time curve.
b) Average force (Faver): mean of force values recorded during the 30 seconds.
c) Maximum impulse (Imax): highest value of the impulse of force (equation 1) in a single-stroke.
d) Average impulse (Iaver): quotient of the sum of the single-stroke impulse and the number of strokes performed during the 30-second tethered swim.

Both velocity-time and force-time curves were examined and 10 successive strokes were chosen for further analysis. The selected strokes occurred during mid-testing. Intra-cyclic velocity variation and Intra-cyclic force variation were analysed as Morouço et al. (2017) previously described:

$$dv = \frac{\sqrt{\frac{\sum_i (v_i - \bar{v})^2 \cdot F_i}{n}}}{\frac{\sum_i v_i \cdot F_i}{n}} \cdot 100$$

(2)

Where *dv* represents the intra-cyclic variation of the horizontal velocity of the hip, *v* represents the mean swimming velocity, *vi* represents the instantaneous swimming velocity, *Fi* represents the acquisition frequency, and *n* is the number of measured strokes. In order to calculate *df* the same equation was adapted using the force parameters obtained in the TS test instead of the velocity parameters.

Total time, mean velocity, partial time, partial mean time, stroke length and stroke rate recorded with ASPA were analysed using FAICO. Data were exported to an Excel spread sheet.

The RPE was assessed verbally, after the trial, using the adapted Borg's scale with incremental descriptors of the perception of effort, ranging from 1 (no exertion at all) to 10 (maximal exertion) (Borg, 1982).

2.6. Statistical analysis

The normality of all distributions was verified using Kolmogorov-Smirnov test and visual inspection of histograms. For analytical purpose, neperian logarithm of maximum force at zero velocity was calculated. Parametric statistical analysis was adopted. Repeated measures ANOVA was carried out to determine the difference in tethered variables after performing the 4 different trials and between SV, SR and RPE in performance test. Bivariate Pearson's correlation coefficients (r) were determined between selected variables, and simple linear regression analyses were applied to evaluate the potential associations. The magnitude of differences in SR and RPE between 25m, 50m and 100m free swimming and the 30s TS at zero velocity, 0,926 m/s, 1,124 m/s, 1,389 m/s water flow velocity was evaluated by a paired-sample t-test. The effect sizes (d) of the obtained differences were calculated and categorized (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 23.0 (Chicago, IL, USA). The level of statistical significance was set at $p<0,05$.

3. RESULTS

In **table 1** it is possible to observe the mean ± SD values for the tethered force, grouped by water flow, performance test variables and RPE. Repeated measures ANOVA analysis revealed significant differences for average force ($F_{3,13}$=207,318, p<0,001), maximum force ($F_{3,13}$=73,631, p<0,001, average impulse ($F_{3,13}$=101,122, p<0,001), maximum impulse ($F_{3,13}$=97,713, p<0,001) and *df* ($F_{3,13}$=14,169, p<0,001) , between the 4 water flow velocities, it is also revealed significant differences for SV ($F_{2,14}$=211,471, p<0,001), between the 3 distances swum. Stroke rate was not significant different in TS ($F_{3,13}$=0,076, p=0,972) but it was significant different in performance test ($F_{2,14}$=25,311, p<0,001). Moreover, RPE were significant different at the performance test ($F_{2,14}$=44,596, p<0,001). However, RPE for TS test were not significant different ($F_{3,13}$=2,402, p=0,115). Post hoc showed that tethered forces variables values were higher swimming at lower velocity (p<0,001), except *df*, that was lower when the force increases (p<0,001). Velocity in 25m were higher than velocity in 50m and 100m (p<0,001). It showed as well that SR was higher in 25m than in 50m and 100m (p<0,001) and RPE was higher in 100m than in 25m and 50m (p<0,001).

Table 2 shows Pearson´s correlation of TS variables at different water flow velocities and free swimming performance. Positive associations of velocity in 25m with average force, maximum force, average impulse and maximum impulse at 1,329 m/s water flow velocity (β= 0,60, β =0,67, β = 0,55 and β =0,52; p=0,013, p= 0,004, p=0,029 and p=0,037 respectively) (figure 6), maximum force were also positive associated with velocity in 50m (β =0,52; p=0,039). Average force, maximum force and maximum impulse at 1,124 m/s water flow velocity were also positive associated with velocity in 25m (β =0,57, β =0,52 and β =0,63; p=0,023, p=0,038 and p=0,009 respectively).

Otherwise, there was no significant relationship between *df* and *dv* with swimming performance.

Intra-cyclic force variation at zero velocity, 0,926 m/s, 1,124 m/s, 1,389 m/s water flow velocity presented much higher values than intra *dv* ($p<0{,}001$;d=4,27, d=4,19, d=3,09, d=3,84 respectively). Significant difference between SR obtained in performance test and tethered test, except SR between 50 m and tethered swimming at zero velocity, 0,926 m/s, 1,124 m/s, 1,389 m/s water flow velocity (table 3). RPE obtained in performance test and tethered test presented also significant difference, except RPE between 50 m and tethered swimming at zero velocity, 0,926 m/s, 1,124 m/s, 1,389 m/s water flow velocity (table 4).

Representative tethered force profiles for the four water flows are shown in figure 7. An upward trace arises when the swimmer increases the force exertion. In contrast, a downward trace happens when the force exertion decreases.

4. DISCUSSION

The main finding of this study was that TS variables measured at different water flow velocities was positively associated to 25m, 50m and 100m SV. Stating that our results confirm previous evidence, this association was higher as water flow velocity increased and swimming distance decreased.

Vorontsov et el. (2006) found similar results, comparing pulling force at zero velocity and 8 different water flow velocities with 100m competitive SV. They found significant association between all the pulling forces measured at every different water flow velocity and 100m swimming performance. According to our results, the association was higher as the water flow increased. Nevertheless, their association was higher than our results show. This difference might be because they used competitive SV in a 50m pool, while we used SV measured in a 25m pool, where turning might affect the outcome (Veiga, Roig, & Gómez-Ruano, 2016). Water backflow also might have affected our results, creating turbulent water around the swimmer (Maglischo, Maglischo, Sharp, Zier, & Katz, 1984) (figure 8). That turbulent water may have diminished force exertion. However, they used a more sophisticated swimming flume without evident water backflow.

Comparing our results at zero velocity with previous studies it is not clear yet which is the best tethered parameter. Our results showed average force as a reliable parameter to estimate SV as Taylor, Lees, Stratton, & MacLaren, (2001) proposed. However, they stated that average force was the only parameter able to estimate swimming performance, while our results showed maximum impulse as a better estimator. Those results are in line with more recent studies who stated that impulse is the most accurate parameter at zero velocity (Amaro et al., 2014; Morouço et al., 2014).

As previously mentioned, different results have been presented regardless *dv*. Our results are in line with those presented by Psycharakis, Naemi, Connaboy, McCabe, & Sanders (2010). We did not found association between *dv* and SV. The main difference with those studies that found association is that we established a lineal association. Barbosa et al. (2006) claimed that polynomial model presents better association than lineal models. Morouço et al. (2017) found association by a second order polynomial. In the same study they showed better association between *df* and performance than *dv* and performance. The relationship between *df* and performance were lineal. We did also found better association between *df* variation and SV than *dv* and performance; however, none of them were significant (p>0,05). The difference may have been in the methodology, since they used fully tethered swimming while we restricted leg action during using an arm stroke TS. Morouço, Marinho, Izquierdo, Neiva, & Marques (2015) estimated the relative contributions of arm stroke in tethered swimming, it was 70,3% for males, showing a considerable difference between fully TS and arm stroke TS.

Stroke Rate and rate of perceived effort did not differed significantly between the 30 seconds tethered test at zero velocity, 0,926 m/s, 1,124 m/s, 1,389 m/s water flow velocity and 50m free swimming. Those results are according with previous studies, confirming that 30 seconds of TS replicate the effort of a 50m free swimming (Morouço et al., 2014). However, our results showed significant difference between the 30 seconds tethered test at zero velocity, 0,926 m/s, 1,124 m/s, 1,389 m/s water flow velocity and 25m and 100m free swimming. Thus, we can assume that 30 seconds in tethered swimming is not able to replicate the effort in those given distance. On the other hand, the results presented by Kalva-Filho et al., (2015) may suggests that 15 or 60 seconds in tethered test may replicate the effort of a 25m and 100m respectively.

In addition, this is the first study investigating the association between tethered variables at zero velocity, 0,926 m/s, 1,124 m/s, 1,389 m/s water flow velocity and 25m, 50, and 100m SV, obtaining better association between force variables and performance at higher water flow velocity.

5. LIMITATIONS, STRENGTHS AND FUTURE STUDIES

Several limitations need to be acknowledged: 1) using a low cost swimming flume did not allow us to measure at higher water flow velocities, since the turbulent water created would affect the measurement considerably, as we could verified in a previous pilot study; 2) we had to exclude the leg action during tethered swimming to prevent the feet from touching the wire and interfering; 3) we did not be able to measure physiological variables as heart rate or blood lactate; 4) maximum propulsive moment of the stroke were not measured.

On the other hand: 1) we did all the test in the same place, so swimmers did not have to move from the venue; 2) to our knowledge it is the first study to analyse the association between several tethered swimming variables and performance in 3 different distance.

We have already design a new system that will allow us to measure fully tethered swimming without any worry about touching the wire. We are also looking for a new biomechanical parameter that associated propulsion and resistance, valid and more accurate to evaluate performance. We will look for different tethered test duration that represents the same efforts to other competitive distances. A relationship with the force and power measurements using land instruments, it should be implemented in the near future. Maximum propulsive moment of the stroke will be taken in to account for future studies.

6. CONCLUSIONS

Our study confirms that TS measured in a swimming flume with a high water flow velocity is a more accurate tool to associate with performance than TS at zero velocity. Average force and maximum impulse at zero velocity are both associated with short sprint performance. *Dv* and *df* were not associated with performance. 30 second tethered test correspond with 50m free swimming; however, it do not correspond with 25m and 100m free swimming.

7. PRACTICAL IMPLICATIONS

Our results will help swimmers to evaluate their performance, comparing their results during the whole season. It will help coaches to plan and quantify the loads, based on the swimmer´s shape. Even though a swimming flume is expensive, there are already many places in the world with that equipment so it will help especially to elite swimmers. Thirty second TS will allow to those swimmers that do not have the chance to train in a 50m pool, to simulate the same effort to a 50m in that kind of pool, without the turn effect.

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9. REFERENCES

1. Akis, T., & Orcan, Y. (2004). Experimental and analytical investigation of the mechanics of crawl stroke swimming. *Mechanics Research Communications*, *31*(2), 243–261. https://doi.org/10.1016/j.mechrescom.2003.07.001
2. Amaro, N. M., Morouço, P. G., Marques, M. C., Fernandes, R. J., & Marinho, D. A. (2017). Biomechanical and bioenergetical evaluation of swimmers using fully-tethered swimming: A qualitative review. *Journal of Human Sport and Exercise*, *12*(4), 1346–1360. https://doi.org/10.14198/jhse.2017.124.20
3. Amaro, N., Marinho, D. a., Batalha, N., Marques, M. C., & Morouço, P. (2014). Reliability of Tethered Swimming Evaluation in Age Group Swimmers. *Journal of Human Kinetics*, *41*(1), 155–162. https://doi.org/10.2478/hukin-2014-0043
4. Barbosa, A. C., de Souza Castro, F., Dopsaj, M., Cunha, S. A., & Júnior, O. A. (2013). Acute responses of biomechanical parameters to different sizes of hand paddles in front-crawl stroke. *Journal of Sports Sciences*, *31*(9), 1015–1023. https://doi.org/10.1080/02640414.2012.762597
5. Barbosa, T. M., Bragada, J. A., Reis, V. M., Marinho, D. A., Carvalho, C., & Silva, A. J. (2010). Energetics and biomechanics as determining factors of swimming performance: Updating the state of the art. *Journal of Science and Medicine in Sport*, *13*(2), 262–269. https://doi.org/10.1016/j.jsams.2009.01.003
6. Barbosa, T. M., Lima, F., Portela, A., Novais, D., Machado, L., Colaço, P., … Vilas-Boas, J. P. (2006). Relationships between energy cost, swimming velocity and speed fluctuation in competitive swimming strokes. *Portuguese Journal of Sport Sciences*, *6*(2), 192–194.
7. Borg, G. A. (1982). Psychophysical bases of perceived exertion. *Med Sci Sports Exerc*, *14*(5), 377–381. https://doi.org/10.1249/00005768-198205000-00012

8. Cohen, J. (1988). *Statistical power analysis for the behavioural sciences*. Hillsdale, NJ: Lawrence Erlbaum Associates.
9. Dominguez-Castells, R., Izquierdo, M., & Arellano, R. (2013). An updated protocol to assess arm swimming power in front crawl. *International Journal of Sports Medicine*, *34*(4), 324–329. https://doi.org/10.1055/s-0032-1323721
10. Dopsaj, M., Matkovíc, I., & Zdravkovíc, I. (2000). The relationship between 50m—Freestyle results and characteristics of tethered forces in male sprinters: A new approach to tethered swimming test. *Phys Educ Sport*, *1*, 15–22.
11. Kalva-Filho, C. A., Zagatto, A. M., Araújo, M. I. C., Santiago, P. R. P., Da Silva, A. S. R., Gobatto, C. A., & Papoti, M. (2015). Relationship Between Aerobic and Anaerobic Parameters From 3-Minute All-Out Tethered Swimming and 400-m Maximal Front Crawl Effort. *The Journal of Strength & Conditioning Research*, *29*(1), 238–245.
12. Keskinen, K. L., Tilli, L. J., & Komi, P. V. (1989). Maximum velocity swimming: Interrelationships of stroking characteristics, force production and anthropometric variables. *Scand J Sport Sci*, *11*, 87–92.
13. Kjendlie, P. L., & Thorsvald, K. (2006). A tethered swimming power test is highly reliable. *Portuguese Journal of Sport Sciences*, *6*(2), 231–233.
14. Knudson, D. V. (2009). Correcting the use of the term "power" in the strength and conditioning literature. *Journal of Strength and Conditioning Research*, *23*(6), 1902–8. https://doi.org/10.1519/JSC.0b013e3181b7f5e5
15. Leblanc, H., Seifert, L., Tourny-Chollet, C., & Chollet, D. (2007). Intra-cyclic distance per stroke phase, velocity fluctuations and acceleration time ratio of a breaststroker's hip: A comparison between elite and nonelite swimmers at different race paces. *International Journal of Sports Medicine*, *28*(2), 140–147.

https://doi.org/10.1055/s-2006-924205

16. Maglischo, C. W., Maglischo, E. W., Sharp, R. L., Zier, D. J., & Katz, A. (1984). Tethered and nontethered crawl swimming. *Sports Biomechanics*, 163–176.
17. Marinho, D. A., Silva, A. J., Reis, V. M., Barbosa, T. M., Vilas-Boas, J. P., Alves, F. B., … Rouboa, A. I. (2011). Three-dimensional CFD analysis of the hand and forearm in swimming. *Journal of Applied Biomechanics*, *27*(1), 74–80. https://doi.org/10.1123/jab.27.1.74
18. Morouço, P. G., Barbosa, T., Arellano, R., & Vilas-Boas, J. P. (2017). Intra-Cyclic Variation of Force and Swimming Performance. *International Journal of Sports Physiology and Performance*, *0*(0), 1–20. https://doi.org/Doi: 10.1123/ijspp.2017-0223
19. Morouço, P. G., Marinho, D. A., Izquierdo, M., Neiva, H., & Marques, M. C. (2015). Relative Contribution of Arms and Legs in 30 s Fully Tethered Front Crawl Swimming. *BioMed Research International*, *2015*. https://doi.org/10.1155/2015/563206
20. Morouço, P. G., Marinho, D. A., Keskinen, K. L., Badillo, J. J., & Marques, M. C. (2014). Tethered Swimming Can Be Used to Evaluate Force Contribution for Short-Distance Swimming Performance. *Journal of Strength and Conditioning Research*, *28*(11), 3093–3099.
21. Morouço, P., Keskinen, K. L., Vilas-Boas, J. P., & Fernandes, R. J. (2011). Relationship between tethered forces and the four swimming techniques performance. *Journal of Applied Biomechanics*, *27*(2), 161–169. https://doi.org/10.1123/jab.27.2.161
22. Narita, K., Nakashima, M., & Takagi, H. (2017). Developing a methodology for estimating the drag in front-crawl swimming at various velocities. *Journal of*

Biomechanics, *54*, 123–128. https://doi.org/10.1016/j.jbiomech.2017.01.037

23. Psycharakis, S. G., Naemi, R., Connaboy, C., McCabe, C., & Sanders, R. H. (2010). Three-dimensional analysis of intracycle velocity fluctuations in frontcrawl swimming. *Scandinavian Journal of Medicine and Science in Sports*, *20*(1), 128–135. https://doi.org/10.1111/j.1600-0838.2009.00891.x
24. Ruiz-Teba, A. (2015). *Biomechanical and physiological responses in four crawl-stroke flume swimming conditions*. University of Granada.
25. Schleihauf, R. E. (1979). A hidrodynamic analysis of swimming propulsion. *Swimming III*, *8*, 70–109.
26. Takagi, H., Sugimoto, S., Nishijima, N., & Wilson, B. D. (2004). Diferences in Stroke Phases, Arm-Leg Coordination and Velocity Fluctuation due to Event, Gender and Performance Level in Breaststroke. *Sports Biomechanics*, *3*, 15–27.
27. Taylor, S., Lees, A., Stratton, G., & MacLaren, D. (2001). Reliability of force production in tethered freestyle swimming among competitive age-group swimmers. *Journal of Sport Sciences*, *19*, 12–13.
28. Veiga, S., Roig, A., & Gómez-Ruano, M. A. (2016). Do faster swimmers spend longer underwater than slower swimmers at World Championships? *European Journal of Sport Science*, *16*(8), 919–926. https://doi.org/10.1080/17461391.2016.1153727
29. Vilas-Boas, J. P., Fernandes, R. J., & Barbosa, T. M. (2011). Intra-cycle velocity variations, swimming economy, performance and training in swimming. In *The world book of swimming: from science to performance* (pp. 119–134). New York: Nova Science Publishers.
30. Vorontsov, A., Popov, O., Binevsky, D., & Dyrko, V. (2006). The assessment of specific strength in well trained male athletes during tethered swimming in the swimming flume. *Rev Port Cienc Desp*, 275–7.

Table 1. Mean ± SD values for the tethered force variables, grouped by water flow velocity, performance test variables and rate of perceived scale.

	Water flow velocity: 0 m/s	Water flow velocity: 0,926 m/s	Water flow velocity: 1,124 m/s	Water flow velocity: 1,389 m/s	25m	50m	100m
Average Force (N)	93,20 ± 16,92	60,14 ± 18,23	43,89 ± 15,32	35,49 ± 15,23			
Maximum Force (N)	214,58 ± 48,66	156,55 ± 37,00	125,14 ± 38,86	110,11 ± 36,18			
Average Impulse (N*s)	50,16 ± 10,92	31,97 ± 8,76	23,56 ± 8,23	18,80 ± 7,89			
Maximum Impulse (N*s)	78,75 ± 13,70	58,83 ± 13,65	47,28 ± 11,21	39,74 ± 10,44			
Intra Cyclic Force Variation	56,17 ± 11,52	67,30 ± 15,06	70,81 ± 19,31	75,75 ± 16,57			
RPE	8,25 ± 1,06	8,13 ± 0,95	8,56 ± 0,72	8,56 ± 0,96	7,38 ± 0,80	8,69 ± 0,60	9,44 ± 0,62
Stroke Rate (Hz)	0,92 ± 0,10	0,92 ± 0,08	0,92 ± 0,08	0,92 ± 0,10	1,01 ± 0,13	0,92 ± 0,09	0,81 ± 0,05
Swimming Velocity (m/s)					1,84 ± 0,05	1,80 ± 0,06	1,66 ± 0,06

Table 2: Pearson´s correlation of tethered swimming variables at different water flow velocities and free swimming performance.

		Water flow velocity: 0 m/s					Water flow velocity: 0,926 m/s					Water flow velocity: 1,124 m/s					Water flow velocity: 1,389 m/s					
		Faver	Fmax	Iaver	Imax	df	Faver	Fmax	Iaver	Imax	df	Faver	Fmax	Iaver	Imax	df	Faver	Fmax	Iaver	Imax	df	dv
SV 25m	r	**0,435***	0,271	0,196	**0,455***	-0,299	**0,436***	0,414	**0,439***	**0,445***	-0,204	**0,565***	**0,523***	**0,483***	**0,627****	-0,292	**0,603****	**0,673****	**0,546***	**0,523***	-0,033	0,103
	p	**0,046**	0,155	0,233	**0,038**	0,130	**0,046**	0,055	**0,044**	**0,042**	0,224	**0,011**	**0,019**	**0,029**	**0,005**	0,136	**0,007**	**0,002**	**0,014**	**0,019**	0,451	0,352
SV 50m	r	0,268	0,138	,083	,380	-0,290	0,222	0,244	0,229	0,291	-0,133	0,415	0,418	0,359	**0,472***	-0,319	**,476***	**0,520***	**0,465***	0,424	-0,213	-0,111
	P	0,158	0,306	0,380	0,073	0,138	0,204	0,181	0,196	0,137	0,311	0,055	0,053	0,086	**0,032**	0,114	**0,031**	**0,020**	**0,035**	0,051	0,214	0,341
SV 100m	r	0,351	0,187	0,172	**0,442***	-0,216	0,263	0,228	0,302	0,298	-0,248	0,358	0,357	0,322	**0,494***	-0,376	0,396	**0,435***	0,415	0,405	-0,238	-0,027
	p	0,092	0,244	0,262	**0,043**	0,211	0,162	0,198	0,128	0,131	0,177	0,086	0,088	0,112	**0,026**	0,076	0,064	**0,046**	0,055	0,060	0,187	0,460

Faver: average force; Fmax: maximum force; Iaver: average impulse; Imax: maximum impulse; df: intra-cyclic force variation; dv: intra-cyclic velocity variation; SV25m: swimming velocity in 25 m; SV50m: swimming velocity in 50m; SV100m: swimming velocity in 100m.

* $p<0,05$. **$p<0,01$..

Table 3: Difference between stroke rate obtained in performance test and tethered test

	SR 25m		SR 50m		SR 100m	
	p	d	p	d	p	d
SR 0 m/s	0,001	0,99	0,794	0,06	<0,001	1,17
SR 0,926 m/s	0,003	0,85	0,979	<0,01	<0,001	1,18
SR 1,124 m/s	0,001	0,97	1	<0,01	<0,001	1,3
SR 1,389 m/s	0,002	0,92	0,962	0,01	<0,001	1,07

SR: stroke rate; p:significance level; d: effect size, categorized (small if $0 \leq |d| \leq 0,5$, medium if $0,5<|d|\leq 0,8$, and large if $|d|>0,8$).

Table 4. Difference between rate of perceived effort obtained in performance test and tethered test.

	RPE 25m		RPE 50m		RPE 100m	
	p	d	p	d	p	d
RPE 0 m/s	0,014	0,69	0,130	0,40	<0,001	1,07
RPE 0,926 m/s	0,029	0,6	0,07	0,48	<0,001	1,21
RPE 1,124 m/s	<0,001	1,30	0,497	0,17	<0,001	1,08
RPE 1,389 m/s	<0,001	1,07	0,497	0,17	<0,001	1,08

RPE: rate of perceived effort; p:significance level; d: effect size, categorized (small if $0 \leq |d| \leq 0,5$, medium if $0,5<|d|\leq 0,8$, and large if $|d|>0,8$).

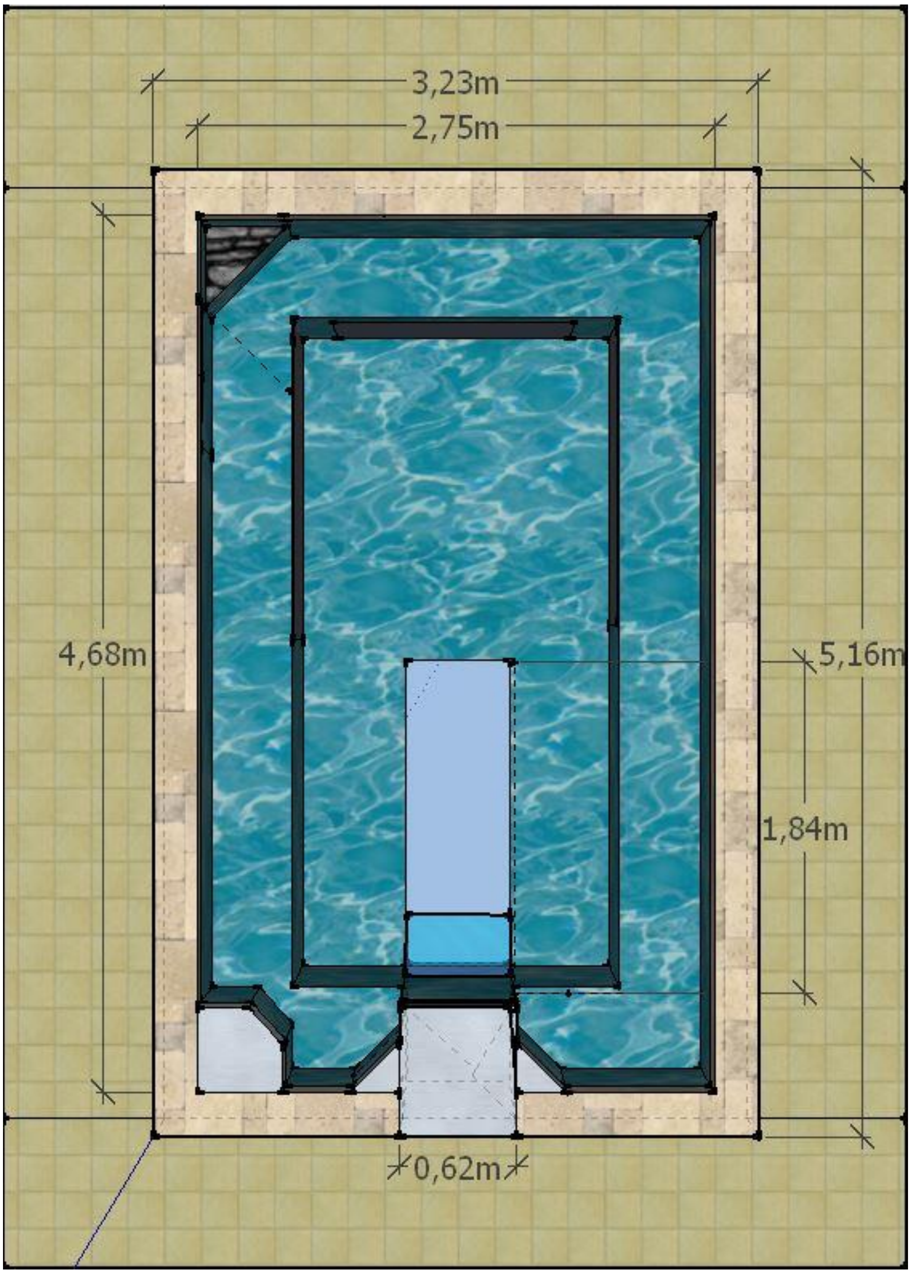

Figure 1. Dimensions of the swimming flume (Endless Poo Elite Techno Jet Swim 7,5, HP, Aston PA, USA) (Ruiz-Teba, 2015).

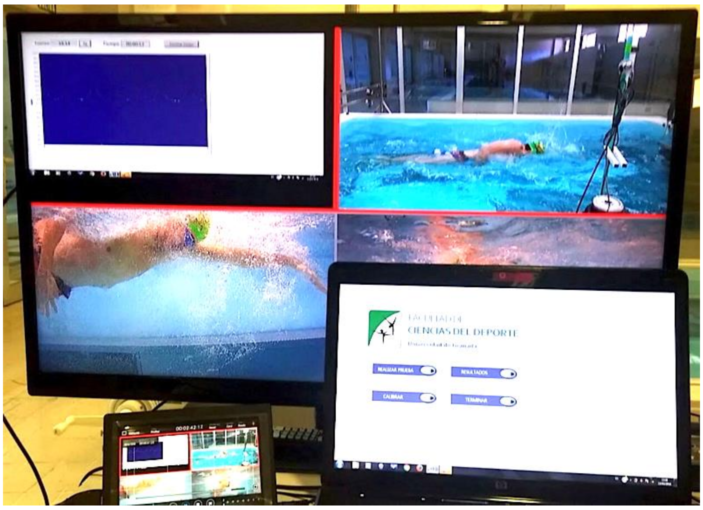

Figure 2. Force recording set up and video camera synchronization. Two underwater video cameras (Marshall,50Hz, full HD, CV225, California, USA) and one video camera out of the water (Sony video camera, 100Hz, Full HD, HDR-CX405, Tokyo, Japan).

Figure 3.Swimming flume overhead image captured with ASPA (Automatic Swimming Performance Analysis) (Ref.: IE_57161).

Figure 4. Speedometer used for the measured of the instantaneous swimming velocity (lineal transducer, Heidenhain, D83301, Traunreut, Germany).

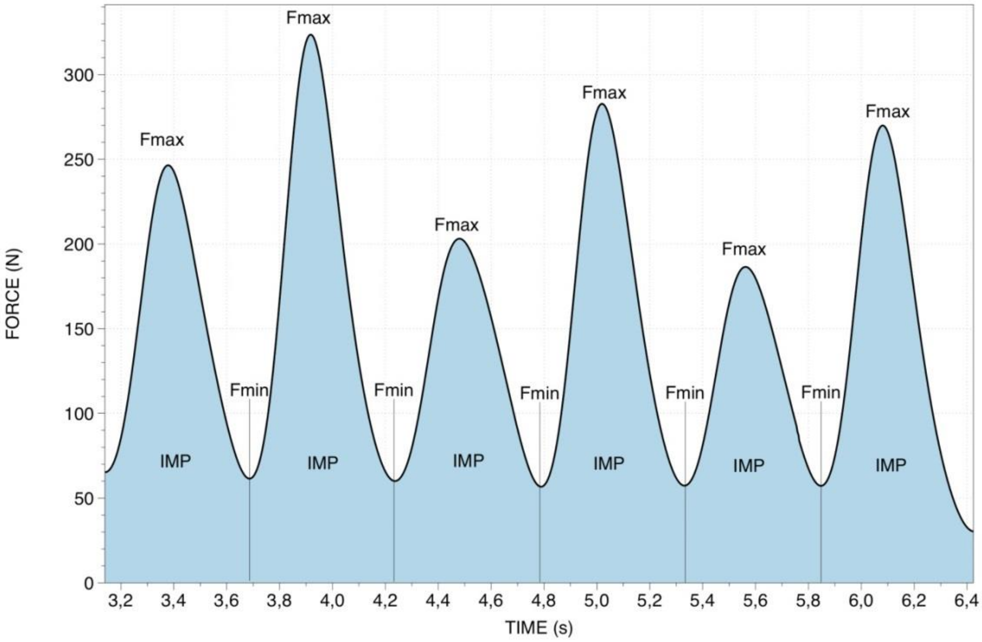

Figure 5. Example of 6 consecutive strokes front crawl force recordings. The main analysis points are shown. Each curve corresponds to each arm. Fmax: maximum force; Fmin: minimum force; IMP: impulse.

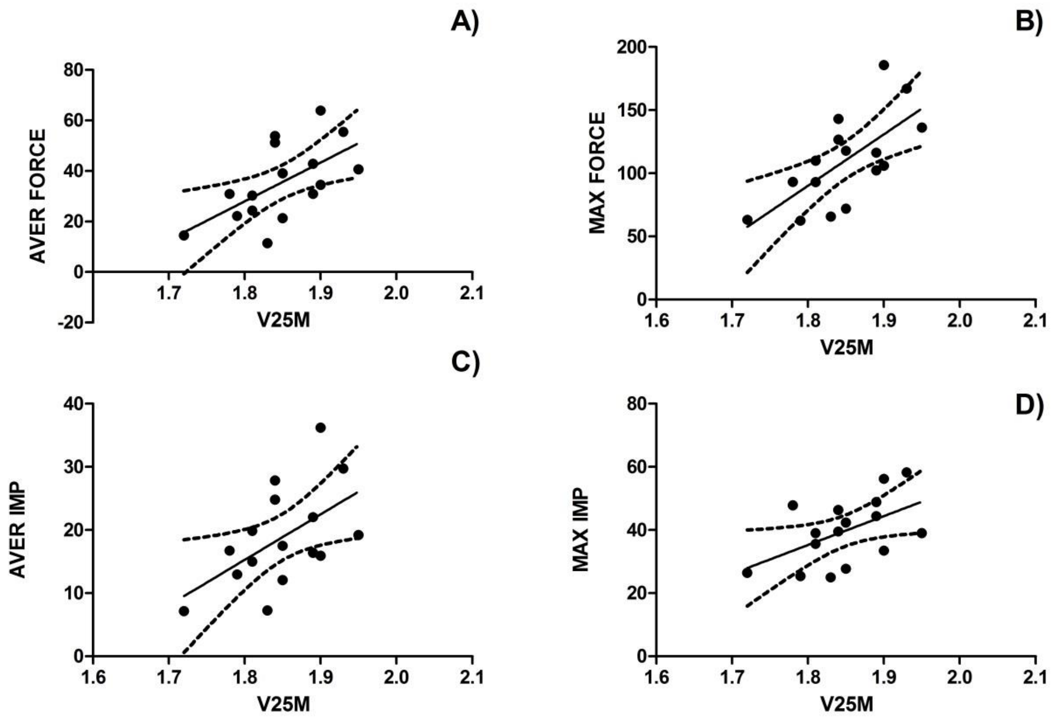

Figure 6. Linear regressions between tethered force variables at 1,389 water flow velocity and velocity in 25m (p<0,05). Individual value and 95% confidence lines are represented. A) AVER FORCE: Average force; B) MAX FORCE: maximum force; C) AVER IMP: average impulse; D) MAX IMP: maximum impulse; V25m: velocity in 25.

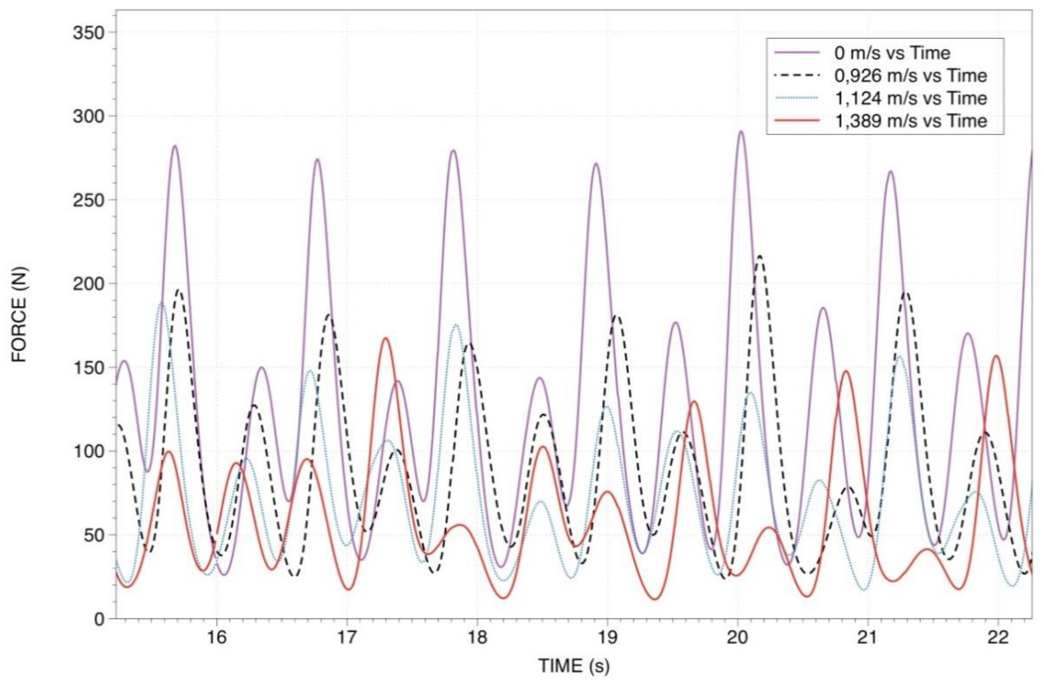

Figure 7. Force recordings comparison of a participant during tethered swimming. The profiles correspond to four water flow velocities in the swimming flume.

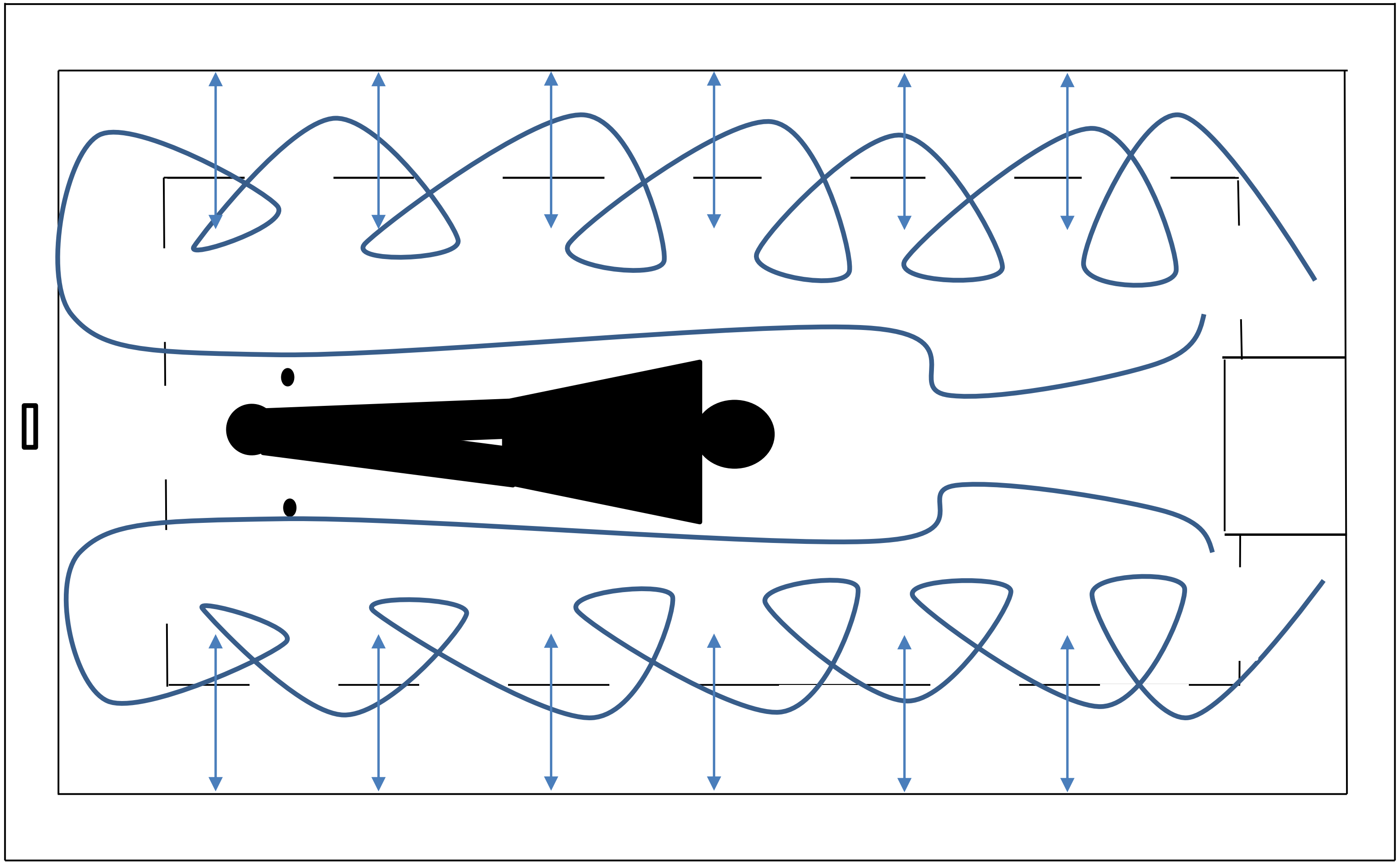

Figure 8. Representation of the water backflow generated in the swimming flume. Vertical lines represent turbulent water.