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The effect of different loads on semi-tethered swimming and its relationship with dry-land performance variables.

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ABSTRACT

Semi-tethered loaded swimming (denoted STLS) has been used widely to develop or test swimmers skills, although its transference to increase performance seems overestimated. In addition, its relationship with dry-land tests remains obscured by imprecise reports. Sixteen competitive male swimmers (age: 18.31 ± 1.42) participated in a two-fold purpose study: Firstly, swimming performance was assessed at different STLS intensities on an adapted Smith Machine. A repeated measures 1-way ANOVA was conducted to find differences between the variables collected through a linear encoder at 15, 30, 45 and 60% of the maximal load (ML). Secondly, the relationships between the swimming velocities and the different sorts of variables obtained on a dry-land arm-stroke strength test were studied by Pearson's correlation coefficient (r). The results showed that less velocity, acceleration and impulse were delivered at high loads ($p < 0.001$). It increased the velocity fluctuation, affecting the swimming patterns adversely. On the other hand, the correlations between velocity-based dry-land variables and swimming velocities ($r = 0.71$) seem to be more suitable to predict swimming performance, rather than strength-based variables ($r = 0.49$). In conclusion, coaches should reconsider using STLS, as little or no benefit may be obtained in performance.

KEY WORDS: Swimming power; Performance assessment; Strength; Dry-land

INTRODUCTION

The development of strength is crucial in swimming competition (Vorontsov, Seifert, Chollet, & Mujika, 2011). For that reason, some authors have tried to find relationships between performance in multi-joint dry-land exercises involving the same muscle system required in swimming and swimming performance. Specifically, some of those studies have focused on strength-based dry-land variables as the repetition maximum test (RM) to predict swimming velocity (Crowe, Babington, Tanner, & Stager, 1999; Garrido et al., 2010; Johnson, Sharp, & Hedrick, 1993), meanwhile some others have observed the relationships between the velocity or power developed on those dry-land exercises with swimming performance (Dominguez-Castells, Izquierdo, & Arellano, 2013; Morouco et al., 2011; Perez-Olea, Valenzuela, Aponte, & Izquierdo, 2018; Ravé et al., 2018). However, in spite of the fact that force production capability is expected to be related to muscle strength and body mass, a key criticism is that testing performance in dry-land conditions may reduce testing effectiveness, as it could not replicate either the power requirements of real swimming nor the biomechanical aspects related to how the swimmer feels the water (Ravé, et al., 2018). The swimmer’s performance does not only depend on the ability to produce large amounts of propulsive forces, but also on the ability to transfer and sustain such outputs to the water as the competition unfolds (dos Santos, Pereira, Papoti, Bento, & Rodacki, 2013). Hence, improving the ability to measure the force produced by the swimmers in the water could allow a real-time control of training and therefore optimize training potential.

In-water resisted modalities as tethered or semi-tethered swimming have been proposed as a valid and reliable tool for the evaluation and control of training given their specificity and sensitivity on monitoring the similar muscular activity than in free swimming (Akis and Orcan, 2004; N. Amaro, Marinho, Batalha, Marques, & Morouco, 2014; Morouco, Marinho, Keskinen, Badillo, & Marques, 2014). However, meanwhile some authors reported small or no limitations caused by tethered modalities (Morouço, Marinho, Izquierdo, Neiva, & Marques, 2015), some others reported critical kinematic changes that could lead to a different trajectory or acceleration of the hands compared with real swimming (Maglischo, Maglischo, Sharp, Zier, & Katz, 1984; Samson, Monnet, Bernard, Lacouture, & David, 2018). On the other hand, as the swimmers need to be attached through a taut cable from their waist to a cell fiber placed on a static point (normally the starting block), some authors have reported that tethered swimmers tend to kick considerably deeper during the trials because it produces a small angle in relation to water surface (N. Amaro, et al., 2014; Maglischo, et al., 1984). In addition, it may not only modify considerably the swimming patterns in low level swimmers or swimmers with no practical experience with these devices, but it may also produce an amount of small combined errors that should be taken into account by the researchers when reporting the results of their tethered measurements (Psycharakis, Paradisis, & Zacharogiannis, 2011). At last, although the forces gathered during a tethered swimming test represent the magnitude of the performed pull drive, and as such, this is a representation of the working potential that has to be realized during free swimming (Dopsaj et al., 2001; Morouco, et al., 2014; Psycharakis, et al., 2011), this method disregards the forces produced to overcome the drag that increases against the displacement of the swimmer (dos Santos, et al., 2013).

For that reason, some authors have tried to solve the aforementioned issues by including a system capable to allow a displacement of the swimmer in the test trial (Dominguez-Castells and Arellano, 2012; Dominguez-Castells, et al., 2013; Hancock, Sparks, & Kullman, 2015; Johnson, et al., 1993; Klauck and Ungerechts, 1997). Klauck and Ungerechts (1997) used a semi-tethered swimming device to calculate the instantaneous mechanical power developed to external loads by registering the revolutions produced by the swimmer motion on a wheel. However, they only reported mean power values and the velocity fluctuations in every stroke were ignored. On the other hand, two studies (Dominguez-Castells and Arellano, 2012; Dominguez-Castells, et al., 2013), tested swimmers in a 12.5 m all-out front crawl swim across a pool connected to an underwater dumbbell by a rope. The velocity and power fluctuations delivered to the dumbbell were successfully calculated through a speedometer wire and a load cell connected to the swimmer; however, the swimmers were unable to sustain a stable swimming velocity and the swimming patterns were adversely affected. In addition, leg kicking was not allowed and it possibly increased body-roll, causing not only asymmetries on the force production, but also a low stability in the water (Mujika and Crowley, 2019; Psycharakis and Sanders, 2010). At last, semi-tethered swimming on adapted Power Racks through pulleys system (Hancock, et al., 2015; Johnson, et al., 1993; Ravé, et al., 2018), has been proposed as a valid and reliable tool because it allows not only to evaluate the power exerted in the water considering the balance between the resistive and propulsive forces originated by the displacement, but also to control the amount of weight lifted and the distance and time required to lift it. However, it is still intriguing to see if the swimmers' skills could be effectively improved through this method due to the possible alterations on the swimming kinetics and kinematics aforementioned reported.

To author's knowledge, two variables such as the intra-cycle velocity variation (dv) and intra-cycle force variation (dF) may contain the key to understand the effectiveness of this method to apply high-resistance practices that do not influence the swimming skills adversely. These variables have been taken from tethered swimming as a way to evaluate the ability of the swimmers to effectively apply the propulsive forces in the water (Morouco, Barbosa, Arellano, & Vilas-Boas, 2017). Higher percentages of these variables would represent a high difference between the maximum and the minimum velocity/force values developed in every stroke as a consequence of a low-efficient application of the forces in the water. Therefore, it would lead in poorer performance because of a lower ability to sustain a stable swimming velocity. On the other hand, as every increase obtained in swimming velocity should be in line with an increase in the force and power production capability (Vorontsov, et al., 2011), it would be of interest for the athletic community an updated perspective of the relationships between the variables collected in dry-land conditions with actual swimming performance . Therefore, the purpose of this study was: i) To present a protocol to assess swimming performance kinetics and kinematics in front crawl with different external loads; ii) to examine the *dF* and *dv* on a STLS test including a displacement; and iii) to study the relationships between the velocity of swimming achieved in every loaded effort and some variables collected by a dry-land exercise.

MATERIAL AND METHODS

EXPERIMENTAL APPROACH TO THE PROBLEM

A quasi-experimental, cross-sectional design was used to explore performance in a STLS test. The study was conducted in two phases: In one session, every participant performed several STLS efforts with increasing loads. During a different session, the participants performed a repetition maximum strength test on a dry-land device simulating arm-stroke of swimming. Performance both in dry-land as in aquatic conditions were assessed from the kinetic/kinematic variables gathered through a linear encoder (Figure 1). Both tests were randomly applied to all the participants to avoid the “fatigue/learning” effect.

In order to reduce the probability of Type I error, the differences in the STLS variables were observed within-subjects at 15, 30, 45 and 60% of the maximal load (ML). On the other hand, the relationships between the mean, maximum and minimum velocity achieved at every STLS effort and the strength- and velocity-based variables achieved in dry-land were studied by Pearson’s coefficient (r). Additionally, this relationship was also explored with the velocity of swimming with no load, acting as a control.

SUBJECTS

Sixteen competitive male swimmers provided signed informed consent and volunteered to participate in this study. The main physical and competitive background characteristics were (mean ± SD): 18.31 ± 1.42 years old; 72.56 ± 9.88 kg of body mass; 1.80 ± 0.03 m of height; 76.28% performance level of the world record (50-m Freestyle, Short course), and ≤ five years of national level competitive participation. Swimmers under the age of 18 were asked to provide written and signed parental consent.

The exclusion criteria included: i) no semi-tethered or in-water resisted practice during the last three months; ii) unable to attend three sessions scheduled in this study; iii) suffering any injury or disease in the past six months. All of the swimmers were reportedly free of the following: drugs, medication, or dietary supplements known to influence physical performance. The tests were scheduled to occur before their daily training regimen, and the subjects were instructed to avoid any physical exertion before testing. All the procedures were performed in accordance with the Declaration of Helsinki with respect to human research, and the study was approved by the Institutional Review Board of the University with the number 852.

PROCEDURES

The participants conducted two incremental strength tests, both in dry-land and aquatic conditions. An isoinertial dynamometer (T-Force Dynamic Measurement System, Ergotech, Murcia, Spain), was used to acquire, display and process velocity-time data during the trials. This system consists of a cable–extension linear velocity transducer interfaced to a personal computer by means of a 14-bit resolution. Signal was acquired at a sampling rate of 1000 Hz. The system was placed on the floor and was connected to the bar of an adapted Smith Machine

(Jim Sports Technology S.L., Lugo, Spain), positioned in the same place. To gather data from every maximal trial on the software application, a taut rope was attached through a home-made pulley system from the Smith Machine's bar to the swimmer's hands (Figure 1A) or hips (Figure 1B). Thus, every maximal effort automatically produced the lifting of the bar and therefore, a displacement registered by the encoder cable. All of the targeted loads were adapted considering the pulley system and previously confirmed with an electronic dynamometer (WeiHeng Electronics Co., Ltd., Guangzhou, China).

On the first day, the participants performed a dry-land strength test designed according to the guidelines of the American College of Sports Medicine (Ferguson, 2014). It was performed on a Smith-Machine (Jim Sports Technology, S.L.) adapted with a home-made pulley system (Barton Marine Equipment Ltd., Whitstable, United Kingdom), which allowed the development of pulling actions away from the system as described by Cuenca-Fernandez, Ruiz-Teba, Lopez-Contreras, & Arellano (2018). The participants started the exercise in prone position on an inclined bench (45º from vertical) with both arms horizontally extended to the front and each hand holding a handle from the pulley system (Figure 1A). They were asked to perform a complete shoulder extension at maximal velocity, return to the starting position in a controlled manner, maintain the position for 0.5 seconds, and perform a second repetition. Every participant had to complete 2 repetitions with each load, increasing every 2 minutes. Through the linear encoder software, it was possible to obtain a prediction of the RM obtained from the first repetition. Therefore, the increments of the load were 10 kg at the beginning of the test and 5 kg later (close to the maximal load).The test finished with the last load they could lift completely, and it was considered as the arm-stroke RM of the subjects (39.18 ± 4.68 kg). The relative load coefficient (Relative_RM) was obtained by dividing the RM value achieved by each participant by their body weight. These two variables were considered as the strength-based dry-land variables. The additional velocity-based variables such as Mean propulsive velocity (MPV), Mean propulsive power (MPP) and Mechanic impulse (IMP), were directly provided by the encoder.

On a second day, the participants moved on an experimental setting placed in a 25 m indoor pool (with water and air temperatures of 28.2 and 28.9º C, respectively). During this session, the swimming front crawl velocity with no load (NoLoadV) of the participants was collected. Each swimmer performed a 400m standardized warm-up consisting of 2x100m easy freestyle swim with 2 starts from the wall; 2x50m front crawl swim (12`5 fast; 12’5 smooth) and 100m front crawl at a normal pace followed by a dynamic stretching protocol both for the upper and the lower limbs as described by Cuenca-Fernandez, et al. (2018). Subsequently, they were tested on an in-water 25m all out swimming effort. One digital video camera (Sony Video Camera, 50Hz; Sony Electronics Inc., Tokyo, Japan), was installed on an underwater window at the poolside. This camera recorded the phase from 5 to 10 m. After the test, the velocity values were obtained from the underwater video files in Kinovea (Kinovea, version 0.7.10, France), as the distance from 5 to 10 m divided by the time elapsed during such action (1.75 ± 0.08 m/s). After that, the swimmers were given a first experience of two efforts in the semi-tethered device.

During a third session, the participants performed the same warm-up protocol and after 6 min of rest, they started the first trial of the STLS. The loads of the STLS were applied on the bar of an adapted Smith Machine connected to the swimmer’s hip through a taut rope (Figure 1B). An in-water start was used and swimmers were instructed to reduce gliding. Although a previous study suggested that breathing patterns seem to not influence symmetry or performance in tethered swimming (N. M. Amaro, Morouço, Marques, Fernandes, & Marinho, 2017), the participants of this study were instructed to hold their breath during the effort in order to avoid any possible influence of this action on the encoder recordings. The test started with 1 kg of load (after the pulley system), and it was increased by successive 1 kg increments. Every trial ended when the swimmers reached the maximal extension of the rope (15 m) and all the efforts had time duration of between 10 to 20 seconds. Six minutes of rest were given between trials (Hancock, et al., 2015). As every swimming effort produced the lift of the bar, it allowed to obtain through the encoder the velocity of swimming regarding the load added to the bar. The test finished when the lift of the bar produced swimming velocities under 0.65-0.55 m/s, as previous research recommended it avoidable (Dominguez-Castells and Arellano, 2012). The percentage of load pulled was estimated for every participant as the percentage of velocity loss regarding the velocity achieved with no load (Gonzalez-Badillo and Sanchez-Medina, 2010). Under this basis, the power/velocity vs. load curves were calculated at 15, 30, 45 and 60% ML. To avoid any effect of the impulse of the swimmer from the wall and the force asymmetries expected on the first cycles of the maximal swimming efforts (Morouço, Marinho, Fernandes, & Marques, 2015), the first 4 arm-strokes were excluded and the 10 consecutive arm-stroke cycles were selected for further analysis.

(Please insert Figure 1 near here)

VARIABLES MEASURED

Average instantaneous velocity and acceleration were acquired from the encoder at a sampling rate of 1000Hz. Velocity and acceleration-time curves were smoothed using a fourth order Butterworth low pass digital filter, with a cut off frequency of 10 Hz, defined according to residual analysis (residual error versus cut-off frequency). The variations on the acceleration curves with respect to time were used to identify the arm-strokes performed by the swimmer. Every curve registered on the acceleration values above zero was considered as a one arm stroke. The maximal and minimum values of velocity were calculated as means ± SD from every arm stroke, obtained directly through the encoder used in 10 consecutive arm stroke cycles ($m \cdot s^{-1}$). The distance covered in 10 strokes (DC10St) was directly calculated as the time to complete 10 strokes (T10St) multiplied by the velocity achieved.

The force delivered to the load was calculated according to Newton's second law (Equation 1), where *m* stands for the load lifted on the Smith Machine in each situation and *a* stands for the instantaneous variations on the acceleration registered by the encoder in the Smith Machine's bar while lifting. The swimming power delivered to the load (average/peak) was calculated as the force (average/peak) multiplied by the velocity delivered (average/peak).

$$F = m \cdot a \qquad \text{Equation 1}$$

The impulse was calculated as the mean ± SD of the values obtained in every single arm stroke according to the equation 2. Where *s* stands for the beginning of the stroke (instant of the force change), *e* for the end of the stroke and *F* stands for the force; Δt was 1/1000 (frequency of data acquisition: 1000 Hz). The impulse normalized to the weight pulled (ImpRel) was obtained by dividing the absolute values of impulse by the mass of the load pulled (in kg).

$$\sum_{s}^{e} F \cdot \Delta t \qquad \text{Equation 2}$$

The intra-cyclic variation of the horizontal velocity of the hip (dv) and the intra-cyclic variation of the horizontal force exerted by the swimmer to the load pulled (dF), was analyzed as previously described by Morouco, et al. (2017), (Equation 3). Where *x* represents either the mean swimming velocity or force, x_i represents either the instantaneous swimming velocity or force, *Fi* represents the acquisition frequency 1/1000 (frequency of data acquisition: 1000 Hz), and *n* is the number of measured strokes.

$$dv \,\&\, dF = \frac{\frac{\sqrt{\sum i(x_i - \overline{x})^2 \cdot F_i}}{n}}{\frac{\sum i x_i \cdot F_i}{n}} \cdot 100 \quad \text{Equation 3}$$

STATISTICAL ANALYSES

Descriptive statistics were obtained and the data was expressed as mean ± SD, confidence intervals (CIs) (95%). The test-retest reliability (intraclass correlation coefficient [ICC]), within and between observers was analyzed for the *dv*. Five trials (5 digitized by the researcher, and the other 5 digitized by other researchers with experience in the processing computational routine), were conducted on 10 swimmers who completed 4 trials with different loads. The intraobserver ICC ranged between 0.95 (95% CI, 0.92 – 0.99) and 0.96 (95%, 0.92-0.98), and the interobserver ICC ranged from 0.97 (95% CI, 0.96 – 0.98) to 0.99 (95% CI, 0.98 – 0.99) for the tethered measurements.

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). After Shapiro-Wilk testing for normality distribution, repeated measures 1-way ANOVA tests were carried out to find differences between the variables at 15, 30, 45 and 60% of the maximal load (ML). To detect differences between variables, significance was accepted at the alpha ≤ 0.05 level, and paired comparisons were used in conjunction with Holm’s Bonferroni method for controlling type 1 errors.

Pearson product-moment correlation coefficients (r) were used to verify the relationship between the swimming velocities and the different sorts of strength-based and velocity-based variables obtained on the dry-land arm-stroke strength test. All statistical procedures were performed using SPSS 21.0 (IBM Chicago, IL, USA).

RESULTS

Mean, SD, P – values and Effect sizes for all tested STLS variables are presented in Table 1. Most of the variables were adversely affected by the load pulled. The velocity of swimming was different ($F_{3,13}$ = 977.72, p = 0.000) and decreased along with the load pulled. In addition, the time to complete the ten arm-strokes ($F_{3,13}$ = 12.616, p = 0.000) and the distance covered ($F_{3,13}$ = 307.22, p = 0.000) was also affected because both variables were progressively lower when increasing the load. The power values were different depending on the load (Mean: $F_{3,13}$ = 20.345, p = 0.000; Peak: $F_{3,13}$ = 27.158, p = 0.000). The highest mean values were obtained at 45% ML (Power: 57.50 ± 10.94 W) (Figure 2), meanwhile the peaks were both found at some point between 30 and 45% ML. From that point onwards, the power values decreased (Table 1).

The values of Force, Acceleration, Impulse and ImpRel were different in every effort ($p < 0.05$). The highest values of force and impulse were obtained at 60% ML, while the highest values of Acceleration and ImpRel were acquired at 15% ML (Table 1). The *dv* values were different ($F_{3,17}$ = 12.142, P = 0.000), although *post-hoc* only revealed a significant increase at 60% ML ($p < 0.002$) in comparison with the rest of the efforts. Finally, no differences were detected in *dF* as a consequence of increasing the load ($F_{3,13}$ = 1.851, P = 0.188).

(Please insert Table 1 near here)

(Please insert Figure 2 near here)

The correlations between the velocity of swimming and the variables collected in dry-land conditions through the Smith Machine's device are shown in Table 2. Pearson's correlation coefficient detected a moderate to strong relationship between the RM and the Relative_RM of the swimmers and the mean velocity with no load ($r = 0.496$, $p = 0.050$; $r = 0.529$, $p = 0.035$; respectively). Regarding the velocity achieved in the different STLS efforts, the RM only correlated with some swimming velocities manifestations at 60% ML, meanwhile the Relative_RM achieved some correlations at 15 and 30% ML (Table 2). On the other hand, MPV and MPP reached strong and moderate correlations with the mean swimming velocity with no load ($r = 0.709$, $p = 0.002$; $r = 0.564$, $p = 0.023$; respectively). Furthermore, some other correlations were found between these variables with the maximum and minimum velocities achieved in the different STLS efforts (Table 2). The higher the velocity and power applied on the dry-land test, the higher the velocity of swimming, even at different loads. Finally, the IMP acquired on the arm-stroke dry-land exercise, reached a negative correlation with the velocity of swimming with no load ($r = -0.554$, $p = 0.026$) and some of the STLS efforts (Table 2). In this sense, high values of impulse in the dry-land exercise were associated with lower velocities of real swimming, especially with the maximum velocities achieved at 30, 45 and 60% ML ($p < 0.03$).

(Please insert Table 2 near here)

DISCUSSION

One of the purposes of our study was to present an updated protocol to assess semi-tethered swimming performance in front crawl. The power vs. load curves presented an inverted ‘U’ shape (Figure 1), similar to those obtained by previous authors (Dominguez-Castells, et al., 2013; Garcia-Ramos et al., 2016). Nevertheless, although the peak power output was achieved at some point between the 30% ML (67.21 ± 10.79 W) and 45% ML (71.38 ± 10.12 W) ($p = 0.137$), the higher value of mean power was found at 45% ML (Figure 1), and it corresponded to a swimming velocity of 0.95 ± 0.06 m/s. Those values were very similar to the ones obtained by Dominguez-Castells, et al. (2013) (66.49 ± 19.09 W), although they reported lower velocity values (0.75 ± 0.18 m/s). In addition, those results were achieved at a very similar load percentage (47% ML: 3.95 ± 0.79 kg), although in the present study, that load percentage corresponded to a larger load mass (45% ML: 6.00 ± 0.98 kg). The reasons to discuss it are two-fold; At first, it is important to consider that leg kicking was not restricted in our study and it obviously provides significant propulsion (Deschodt, Arsac, & Rouard, 1999; Morouço, Marinho, Izquierdo, et al., 2015). Moreover, it has been noted that leg kicking has a considerable influence on body-roll because it applies a torque on the hip that limits the hip rotation (Sanders and Psycharakis, 2009). Therefore, it may provide a higher stabilization in the development of the swimming movements (Psycharakis and Sanders, 2010). On the other hand, the resistance offered by the added mass may be higher underwater given the quadratic nature of the hydrodynamic drag (Marinho et al., 2009). In such case, the external work was higher not only because of the increases of the load, but also because of the drag offered by the dumbbell when accelerating (Dominguez-Castells, et al., 2013; Hollander et al., 1986).

By contrast, in the study of Johnson, et al. (1993), the resistance of the added mass was applied externally on a power rack, and the values were collected without inhibiting the leg actions. Such a method was more akin to what was applied in this study, however, the peak power output was slightly higher than the maximal values achieved in this study (80 ± 21 W vs. 71.38 ± 10.12 W) and the load eliciting that peak power was significantly superior (7.8 kg) than the range of loads found in our study (4.37 – 6.00 kg). Possibly, since Power was calculated in both studies as (Force · Distance) / Time, the differences would come from the procedure to obtain the Force value. In the study of Johnson, et al. (1993), it was calculated solely as the weight pulled by the swimmers, meanwhile in the present study, the Force values were determined according to Newton's second law ($F = m \cdot a$). Therefore, the values achieved at high loads might have been countered by the low acceleration achieved (Table 1), and therefore, this may have influenced the outcomes obtained in Power.

Furthermore, according to the force-velocity relationship of the skeletal muscle, the outcomes obtained in Force and Impulse could be expected (Table 1), indicating that at very high velocity contractions, it is not easy to accumulate high amounts of force and impulse values and once the resistance loads grow, the force and impulse needed to overcome them increases (Dopsaj, et al., 2001; Garcia-Ramos, et al., 2016; Keskinen, Tilli, & Komi, 1989). Considering that any increase in swimming velocity requires a proportional increase in the applied muscle force to sustain such velocity (Vorontsov, et al., 2011), this fact may reflect an augmented quantity of the propulsive movements conveyed per stroke at high loads, a key that might be of success for sprinters (N. Amaro, et al., 2014; Dopsaj, et al., 2001). However, the loss of velocity and acceleration, together with the reduction of the distance covered and the time in the 10 arm-strokes were not in line with the increases obtained in force and absolute impulse at high loads but in line with the reduction of the Impulse normalized to the load pulled (ImpRel). Therefore, if STLS does not produce any increase on the propulsive skills, but deterioration on them, it should be highly reconsidered when including in-water resisted swimming routines, as little or no benefit may be obtained from them.

In any case, coaches should be aware that the application of different loads in STLS may affect the subjects' performance differently. Lower power production at fast velocities and low loads might indicate a high resistive drag and a low swimming efficiency, meanwhile a low power production at heavy loads and low velocities might indicate deficits in the swimmers strength (Dopsaj, et al., 2001; Johnson, et al., 1993). For that reason, another aim of this study was to examine the intra-cycle velocity (*dv*) and force variation (*dF*) along with the increasing loads. The dv% and dF% represents a balance between propulsive and resistive forces. The higher the dv% and dF% the poorer the performance, as it represents a low-efficient application of the forces in the water (Barbosa et al., 2013). In our study, the highest dv% was obtained at the highest load and lowest velocity. In fact, the deepest variation in dv% was detected between 45 to 60% ML ($p < 0.001$), coinciding also with the loss of swimming power (Table 1). These results were expected. Sustaining high swim velocities is obviously hard while pulling heavy loads because the swimmer is unable to find the impulse needed to overcome the resistance in an unstable environment such as water. It implies increases in power and strength requirements of the muscles (e.g. with speed), which require stiffer tendons to produce optimal efficiency and the required power with a given muscle volume. The greater force generated by muscle is associated with the transmission of more stress through the tendon. Consequently, higher muscle requirements also produce higher fatigue and it may affect the swimming technique adversely (Cuenca-Fernandez, et al., 2018).

Morouco, et al. (2017) reported that swimmers with higher dv% would also present higher dF%. However, the dF% did not change along with the increase of the load (Figure 2), and actually, it seemed to be slightly reduced as a consequence of it. Possibly, as the time to complete the 10 arm-strokes was shorter at higher loads, it indicated that every arm-stroke was not only shorter, but also produced less propulsive impulse. This modification on the stroke patterns may be a consequence of the increased difficulty to transfer the force into the water at maximal or sub-maximal loads and would also be consistent with the results found in the present study for

ImpRel (Table 1). Nevertheless, previous studies have shown that semi-tethered swimmers may increase the coordination index by overlapping the arm strokes, and this effect may reduce the dF% (Dominguez-Castells and Arellano, 2012; Schnitzierl, Seifert, Ernwein, & Chollet, 2008; Seifert, Chollet, & Bardy, 2004). Unfortunately, that variable was not measured in this study and future research should provide more information about this issue, testing also if swimmers with a high dF% may benefit from STLS practice to reduce it.

The associations found between the dry-land variables and the velocity of swimming (Table 2), are not new as previous studies have shown considerable interest in this field (Crowe, et al., 1999; Dominguez-Castells, et al., 2013; Garrido, et al., 2010; Perez-Olea, et al., 2018; Ravé, et al., 2018). In the study of Johnson, et al. (1993), the RM achieved on the *bench press* exercise was correlated with the swimming velocity (r = 0.55), meanwhile in the study of Garrido, et al. (2010), a similar correlation was found (r = 0.58) compared with the load at 6RM. However, both authors pointed out that the nature of the selected exercise was possibly not specific enough to expect that improvements in strength would result in improved swimming performance. In contrast, Crowe, et al. (1999), obtained higher correlations (r = 0.65), between the RM obtained in *lat pull-down* (i.e. in a pulling exercise) and swimming performance measured in 50 meters. For that reason, despite RM being more related with maximum force than with explosive force, the associations between swimming velocity with the RM (r = 0.49) and Relative_RM (r = 0.52) were explored in this study through a pulling exercise, which would support the development of muscular strength in swimmers, as it appears to play an important role in the determination of maximal swim velocity.

Nevertheless, it is worthy of review that while the RM only showed moderate to strong correlations with V60 (r = 0.68) and Vmin60 (r = 0.52) (i.e. at higher loads), the Relative_RM, reached correlations with V15 (r = 0.52), Vmin15 (r = 0.52) and V30 (r = 0.54) (i.e. at lower loads). Since the fact that producing a high percentage of Relative_RM is the greater capacity of force due to lower body weight, the Relative_RM index may reflect with more accuracy the strength abilities of the swimmers (Cuenca-Fernández et al., 2015). Possibly, considering that higher swimming velocities were achieved at low loads (Table 1), the correlation with the Relative_RM index may also reflect that those swimmers presented a lower surface area and hydrodynamic drag than the average (Hollander, et al., 1986). At 60% ML, under a severe reduction of swimming velocity ($p < 0.000$) and consequently in the drag acting against the body (Marinho, et al., 2009), the RM of the swimmers was shown as a predictor to achieve and maintain a higher swimming velocity (Table 2). It may indicate that regardless of their strength abilities, the swimmers with a high value of Relative_RM may presumably offer less drag than the average and it would be more reliable than testing only the RM to predict real swimming performance. Moreover, it would offer a valid and different rationale arguing why studies testing performance in tethered swimming (i.e. with no drag acting against the body) have shown to be more related with the absolute force values rather than with the relative ones (normalized to body mass) (Morouco, et al., 2011).

On the other hand, as movement velocity has shown to be a predictor of loading intensity and strength capability in resistance training (Gonzalez-Badillo and Sanchez-Medina, 2010), different velocity-based perspectives have been carried out to link performance obtained in dry-land conditions with actual swimming. Morouco, et al. (2011), found correlations ($r = 0.68$) between MPP in *lat pull down* and velocity of swimming in 50m. Meanwhile, in the study of Dominguez-Castells, et al. (2013) the maximum power obtained on a dry-land arm-stroke exercise, was relatively similar to maximum swim power ($r = 0.91$), and both of these power values were related to swim velocity ($r = 0.85$, $r = 0.72$). On the other hand, Perez-Olea, et al. (2018) recently demonstrated that the mean velocity reached in a test of maximal number of *pull-ups* correlated with swimming velocity ($r = 0.88$), and the relative loss of velocity during the pull-up test accounted for 84% ($p < 0.001$) of 50m freestyle performance variance. Thus, those results were in agreement with the ones obtained in this study as two of the velocity-based variables, MPV and MPP, correlated with different velocities achieved at different STLS efforts

(Table 2). Meanwhile, the negative correlation obtained between IMP and swimming velocity indicated that for a given force in N, the lower the velocity of the arm-stroke, the higher the time spent to complete the movement. Therefore, considering that swimming is characterized by producing fast movements in a short period of time, especially when sprinting (Seifert, et al., 2004), velocity-based dry-land variables may constitute an effective approach to predict actual swimming performance.

The results of the present investigation have shown that STLS alters the swimming kinetics and kinematics. A reduction of the time spent per stroke is obtained due to loaded swimming and it seems not possible to achieve the higher requirements of force/impulse needed to overcome the high loads. Those alterations seem to be higher from 45% ML onwards, with greater increases in critical variables as dv% which indicated a high difficulty to maintain a constant speed in the water and a deep deterioration in performance. Therefore, STLS should be cautiously administered to include specific high-intensity force development programs, since its transfer to improve the biomechanical skills of the swimmers seems questionable. Regarding the results obtained in the dry-land test, the swimmers with higher index of relative strength may obtain better results in STLS at low loads and higher speed, although the ability to develop a high amount of absolute strength seems relevant for swimmers. Possibly, as the velocity obtained when pulling a low resistance in the STLS likely reflects the combined contribution of the propulsive skills and minimized body drag, the improvement in either of these components could result in improved swimming performance scores. In any case, swimming performances seem to be better predicted through dry-land exercises which allow the development of high speed and explosive movements, possibly because actual swimming movements are produced quickly and intensely in a short period of time.

This study presented some limitations, as the correlations presented here were obtained according to swimmers' upper limb strength; however, the semi-tethered encoder recordings might not just be from the arm action throughout the underwater stroke, but also from the leg action. On the other hand, although participants had one previous practice with the STLS device, it was possible not enough to get familiarized enough with it. Nevertheless, a simple adaptation of a system used to measure performance in dry-land conditions allowed us to measure performance in swimmers. Moreover, this system has shown to be sensitive in obtaining valuable information about intra-cyclic velocity or force variation, which could lead coaches to focus on improving swimmer’s technique rather than increasing physical conditioning.

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DECLARATION OF INTEREST STATEMENT

No potential conflict of interest was reported by the authors.

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The effect of different loads on semi-tethered swimming and its relationship with dry-land performance variables.

ABSTRACT

Semi-tethered loaded swimming (denoted STLS) has been used widely to develop or test swimmers skills, although its transference to increase performance seems overestimated. In addition, its relationship with dry-land tests remains obscured by imprecise reports. Sixteen competitive male swimmers (age: 18.31 ± 1.42) participated in a two-fold purpose study: Firstly, swimming performance was assessed at different STLS intensities on an adapted Smith Machine. A repeated measures 1-way ANOVA was conducted to find differences between the variables collected through a linear encoder at 15, 30, 45 and 60% of the maximal load (ML). Secondly, the relationships between the swimming velocities and the different sorts of variables obtained on a dry-land arm-stroke strength test were studied by Pearson's correlation coefficient (r). The results showed that less velocity, acceleration and impulse were delivered at high loads ($p < 0.001$). It increased the velocity fluctuation, affecting the swimming patterns adversely. On the other hand, the correlations between velocity-based dry-land variables and swimming velocities ($r = 0.71$) seem to be more suitable to predict swimming performance, rather than strength-based variables ($r = 0.49$). In conclusion, coaches should reconsider using STLS, as little or no benefit may be obtained in performance.

KEY WORDS: Swimming power; Performance assessment; Strength; Dry-land

INTRODUCTION

The development of strength is crucial in swimming competition (Vorontsov, Seifert, Chollet, & Mujika, 2011). For that reason, some authors have tried to find relationships between performance in multi-joint dry-land exercises involving the same muscle system required in swimming and swimming performance. Specifically, some of those studies have focused on strength-based dry-land variables as the repetition maximum test (RM) to predict swimming velocity (Crowe, Babington, Tanner, & Stager, 1999; Garrido et al., 2010; Johnson, Sharp, & Hedrick, 1993), meanwhile some others have observed the relationships between the velocity or power developed on those dry-land exercises with swimming performance (Dominguez-Castells, Izquierdo, & Arellano, 2013; Morouco et al., 2011; Perez-Olea, Valenzuela, Aponte, & Izquierdo, 2018; Ravé et al., 2018). However, in spite of the fact that force production capability is expected to be related to muscle strength and body mass, a key criticism is that testing performance in dry-land conditions may reduce testing effectiveness, as it could not replicate either the power requirements of real swimming nor the biomechanical aspects related to how the swimmer feels the water (Ravé, et al., 2018). The swimmer's performance does not only depend on the ability to produce large amounts of propulsive forces, but also on the ability to transfer and sustain such outputs to the water as the competition unfolds (dos Santos, Pereira, Papoti, Bento, & Rodacki, 2013). Hence, improving the ability to measure the force produced by the swimmers in the water could allow a real-time control of training and therefore optimize training potential.

In-water resisted modalities as tethered or semi-tethered swimming have been proposed as a valid and reliable tool for the evaluation and control of training given their specificity and sensitivity on monitoring the similar muscular activity than in free swimming (Akis and Orcan, 2004; N. Amaro, Marinho, Batalha, Marques, & Morouco, 2014; Morouco, Marinho, Keskinen, Badillo, & Marques, 2014). However, meanwhile some authors reported small or no limitations caused by tethered modalities (Morouço, Marinho, Izquierdo, Neiva, & Marques, 2015), some others reported critical kinematic changes that could lead to a different trajectory or acceleration of the hands compared with real swimming (Maglischo, Maglischo, Sharp, Zier, & Katz, 1984; Samson, Monnet, Bernard, Lacouture, & David, 2018). On the other hand, as the swimmers need to be attached through a taut cable from their waist to a cell fiber placed on a static point (normally the starting block), some authors have reported that tethered swimmers tend to kick considerably deeper during the trials because it produces a small angle in relation to water surface (N. Amaro, et al., 2014; Maglischo, et al., 1984). In addition, it may not only modify considerably the swimming patterns in low level swimmers or swimmers with no practical experience with these devices, but it may also produce an amount of small combined errors that should be taken into account by the researchers when reporting the results of their tethered measurements (Psycharakis, Paradisis, & Zacharogiannis, 2011). At last, although the forces gathered during a tethered swimming test represent the magnitude of the performed pull drive, and as such, this is a representation of the working potential that has to be realized during free swimming (Dopsaj et al., 2001; Morouco, et al., 2014; Psycharakis, et al., 2011), this method disregards the forces produced to overcome the drag that increases against the displacement of the swimmer (dos Santos, et al., 2013).

For that reason, some authors have tried to solve the aforementioned issues by including a system capable to allow a displacement of the swimmer in the test trial (Dominguez-Castells and Arellano, 2012; Dominguez-Castells, et al., 2013; Hancock, Sparks, & Kullman, 2015; Johnson, et al., 1993; Klauck and Ungerechts, 1997). Klauck and Ungerechts (1997) used a semi-tethered swimming device to calculate the instantaneous mechanical power developed to external loads by registering the revolutions produced by the swimmer motion on a wheel. However, they only reported mean power values and the velocity fluctuations in every stroke were ignored. On the other hand, two studies (Dominguez-Castells and Arellano, 2012; Dominguez-Castells, et al., 2013), tested swimmers in a 12.5 m all-out front crawl swim across a pool connected to an underwater dumbbell by a rope. The velocity and power fluctuations delivered to the dumbbell were successfully calculated through a speedometer wire and a load cell connected to the swimmer; however, the swimmers were unable to sustain a stable swimming velocity and the swimming patterns were adversely affected. In addition, leg kicking was not allowed and it possibly increased body-roll, causing not only asymmetries on the force production, but also a low stability in the water (Mujika and Crowley, 2019; Psycharakis and Sanders, 2010). At last, semi-tethered swimming on adapted Power Racks through pulleys system (Hancock, et al., 2015; Johnson, et al., 1993; Ravé, et al., 2018), has been proposed as a valid and reliable tool because it allows not only to evaluate the power exerted in the water considering the balance between the resistive and propulsive forces originated by the displacement, but also to control the amount of weight lifted and the distance and time required to lift it. However, it is still intriguing to see if the swimmers' skills could be effectively improved through this method due to the possible alterations on the swimming kinetics and kinematics aforementioned reported.

To author's knowledge, two variables such as the intra-cycle velocity variation (dv) and intra-cycle force variation (dF) may contain the key to understand the effectiveness of this method to apply high-resistance practices that do not influence the swimming skills adversely. These variables have been taken from tethered swimming as a way to evaluate the ability of the swimmers to effectively apply the propulsive forces in the water (Morouco, Barbosa, Arellano, & Vilas-Boas, 2017). Higher percentages of these variables would represent a high difference between the maximum and the minimum velocity/force values developed in every stroke as a consequence of a low-efficient application of the forces in the water. Therefore, it would lead in poorer performance because of a lower ability to sustain a stable swimming velocity. On the other hand, as every increase obtained in swimming velocity should be in line with an increase in the force and power production capability (Vorontsov, et al., 2011), it would be of interest for the athletic community an updated perspective of the relationships between the variables collected in dry-land conditions with actual swimming performance . Therefore, the purpose of this study was: i) To present a protocol to assess swimming performance kinetics and kinematics in front crawl with different external loads; ii) to examine the *dF* and *dv* on a STLS test including a displacement; and iii) to study the relationships between the velocity of swimming achieved in every loaded effort and some variables collected by a dry-land exercise.

MATERIAL AND METHODS

EXPERIMENTAL APPROACH TO THE PROBLEM

A quasi-experimental, cross-sectional design was used to explore performance in a STLS test. The study was conducted in two phases: In one session, every participant performed several STLS efforts with increasing loads. During a different session, the participants performed a repetition maximum strength test on a dry-land device simulating arm-stroke of swimming. Performance both in dry-land as in aquatic conditions were assessed from the kinetic/kinematic variables gathered through a linear encoder (Figure 1). Both tests were randomly applied to all the participants to avoid the “fatigue/learning” effect.

In order to reduce the probability of Type I error, the differences in the STLS variables were observed within-subjects at 15, 30, 45 and 60% of the maximal load (ML). On the other hand, the relationships between the mean, maximum and minimum velocity achieved at every STLS effort and the strength- and velocity-based variables achieved in dry-land were studied by Pearson’s coefficient (r). Additionally, this relationship was also explored with the velocity of swimming with no load, acting as a control.

SUBJECTS

Sixteen competitive male swimmers provided signed informed consent and volunteered to participate in this study. The main physical and competitive background characteristics were (mean ± SD): 18.31 ± 1.42 years old; 72.56 ± 9.88 kg of body mass; 1.80 ± 0.03 m of height; 76.28% performance level of the world record (50-m Freestyle, Short course), and ≤ five years of national level competitive participation. Swimmers under the age of 18 were asked to provide written and signed parental consent.

The exclusion criteria included: i) no semi-tethered or in-water resisted practice during the last three months; ii) unable to attend three sessions scheduled in this study; iii) suffering any injury or disease in the past six months. All of the swimmers were reportedly free of the following: drugs, medication, or dietary supplements known to influence physical performance. The tests were scheduled to occur before their daily training regimen, and the subjects were instructed to avoid any physical exertion before testing. All the procedures were performed in accordance with the Declaration of Helsinki with respect to human research, and the study was approved by the Institutional Review Board of the University with the number 852.

PROCEDURES

The participants conducted two incremental strength tests, both in dry-land and aquatic conditions. An isoinertial dynamometer (T-Force Dynamic Measurement System, Ergotech, Murcia, Spain), was used to acquire, display and process velocity-time data during the trials. This system consists of a cable–extension linear velocity transducer interfaced to a personal computer by means of a 14-bit resolution. Signal was acquired at a sampling rate of 1000 Hz. The system was placed on the floor and was connected to the bar of an adapted Smith Machine

(Jim Sports Technology S.L., Lugo, Spain), positioned in the same place. To gather data from every maximal trial on the software application, a taut rope was attached through a home-made pulley system from the Smith Machine's bar to the swimmer's hands (Figure 1A) or hips (Figure 1B). Thus, every maximal effort automatically produced the lifting of the bar and therefore, a displacement registered by the encoder cable. All of the targeted loads were adapted considering the pulley system and previously confirmed with an electronic dynamometer (WeiHeng Electronics Co., Ltd., Guangzhou, China).

On the first day, the participants performed a dry-land strength test designed according to the guidelines of the American College of Sports Medicine (Ferguson, 2014). It was performed on a Smith-Machine (Jim Sports Technology, S.L.) adapted with a home-made pulley system (Barton Marine Equipment Ltd., Whitstable, United Kingdom), which allowed the development of pulling actions away from the system as described by Cuenca-Fernandez, Ruiz-Teba, Lopez-Contreras, & Arellano (2018). The participants started the exercise in prone position on an inclined bench (45º from vertical) with both arms horizontally extended to the front and each hand holding a handle from the pulley system (Figure 1A). They were asked to perform a complete shoulder extension at maximal velocity, return to the starting position in a controlled manner, maintain the position for 0.5 seconds, and perform a second repetition. Every participant had to complete 2 repetitions with each load, increasing every 2 minutes. Through the linear encoder software, it was possible to obtain a prediction of the RM obtained from the first repetition. Therefore, the increments of the load were 10 kg at the beginning of the test and 5 kg later (close to the maximal load).The test finished with the last load they could lift completely, and it was considered as the arm-stroke RM of the subjects (39.18 ± 4.68 kg). The relative load coefficient (Relative_RM) was obtained by dividing the RM value achieved by each participant by their body weight. These two variables were considered as the strength-based dry-land variables. The additional velocity-based variables such as Mean propulsive velocity (MPV), Mean propulsive power (MPP) and Mechanic impulse (IMP), were directly provided by the encoder.

On a second day, the participants moved on an experimental setting placed in a 25 m indoor pool (with water and air temperatures of 28.2 and 28.9º C, respectively). During this session, the swimming front crawl velocity with no load (NoLoadV) of the participants was collected. Each swimmer performed a 400m standardized warm-up consisting of 2x100m easy freestyle swim with 2 starts from the wall; 2x50m front crawl swim (12`5 fast; 12’5 smooth) and 100m front crawl at a normal pace followed by a dynamic stretching protocol both for the upper and the lower limbs as described by Cuenca-Fernandez, et al. (2018). Subsequently, they were tested on an in-water 25m all out swimming effort. One digital video camera (Sony Video Camera, 50Hz; Sony Electronics Inc., Tokyo, Japan), was installed on an underwater window at the poolside. This camera recorded the phase from 5 to 10 m. After the test, the velocity values were obtained from the underwater video files in Kinovea (Kinovea, version 0.7.10, France), as the distance from 5 to 10 m divided by the time elapsed during such action (1.75 ± 0.08 m/s). After that, the swimmers were given a first experience of two efforts in the semi-tethered device.

During a third session, the participants performed the same warm-up protocol and after 6 min of rest, they started the first trial of the STLS. The loads of the STLS were applied on the bar of an adapted Smith Machine connected to the swimmer’s hip through a taut rope (Figure 1B). An in-water start was used and swimmers were instructed to reduce gliding. Although a previous study suggested that breathing patterns seem to not influence symmetry or performance in tethered swimming (N. M. Amaro, Morouço, Marques, Fernandes, & Marinho, 2017), the participants of this study were instructed to hold their breath during the effort in order to avoid any possible influence of this action on the encoder recordings. The test started with 1 kg of load (after the pulley system), and it was increased by successive 1 kg increments. Every trial ended when the swimmers reached the maximal extension of the rope (15 m) and all the efforts had time duration of between 10 to 20 seconds. Six minutes of rest were given between trials (Hancock, et al., 2015). As every swimming effort produced the lift of the bar, it allowed to obtain through the encoder the velocity of swimming regarding the load added to the bar. The test finished when the lift of the bar produced swimming velocities under 0.65-0.55 m/s, as previous research recommended it avoidable (Dominguez-Castells and Arellano, 2012). The percentage of load pulled was estimated for every participant as the percentage of velocity loss regarding the velocity achieved with no load (Gonzalez-Badillo and Sanchez-Medina, 2010). Under this basis, the power/velocity vs. load curves were calculated at 15, 30, 45 and 60% ML. To avoid any effect of the impulse of the swimmer from the wall and the force asymmetries expected on the first cycles of the maximal swimming efforts (Morouço, Marinho, Fernandes, & Marques, 2015), the first 4 arm-strokes were excluded and the 10 consecutive arm-stroke cycles were selected for further analysis.

(Please insert Figure 1 near here)

VARIABLES MEASURED

Average instantaneous velocity and acceleration were acquired from the encoder at a sampling rate of 1000Hz. Velocity and acceleration-time curves were smoothed using a fourth order Butterworth low pass digital filter, with a cut off frequency of 10 Hz, defined according to residual analysis (residual error versus cut-off frequency). The variations on the acceleration curves with respect to time were used to identify the arm-strokes performed by the swimmer. Every curve registered on the acceleration values above zero was considered as a one arm stroke. The maximal and minimum values of velocity were calculated as means ± SD from every arm stroke, obtained directly through the encoder used in 10 consecutive arm stroke cycles (m · s^{-1}). The distance covered in 10 strokes (DC10St) was directly calculated as the time to complete 10 strokes (T10St) multiplied by the velocity achieved.

The force delivered to the load was calculated according to Newton's second law (Equation 1), where *m* stands for the load lifted on the Smith Machine in each situation and *a* stands for the instantaneous variations on the acceleration registered by the encoder in the Smith Machine's bar while lifting. The swimming power delivered to the load (average/peak) was calculated as the force (average/peak) multiplied by the velocity delivered (average/peak).

$$F = m \cdot a \qquad \text{Equation 1}$$

The impulse was calculated as the mean ± SD of the values obtained in every single arm stroke according to the equation 2. Where *s* stands for the beginning of the stroke (instant of the force change), *e* for the end of the stroke and *F* stands for the force; Δt was 1/1000 (frequency of data acquisition: 1000 Hz). The impulse normalized to the weight pulled (ImpRel) was obtained by dividing the absolute values of impulse by the mass of the load pulled (in kg).

$$\sum_{s}^{e} F \cdot \Delta t \qquad \text{Equation 2}$$

The intra-cyclic variation of the horizontal velocity of the hip (dv) and the intra-cyclic variation of the horizontal force exerted by the swimmer to the load pulled (dF), was analyzed as previously described by Morouco, et al. (2017), (Equation 3). Where *x* represents either the mean swimming velocity or force, x_i represents either the instantaneous swimming velocity or force, Fi represents the acquisition frequency 1/1000 (frequency of data acquisition: 1000 Hz), and n is the number of measured strokes.

$$dv \,\&\, dF = \frac{\frac{\sqrt{\sum i(x_i - \overline{x})^2 \cdot F_i}}{n}}{\frac{\sum i x_i \cdot F_i}{n}} \cdot 100 \quad \text{Equation 3}$$

STATISTICAL ANALYSES

Descriptive statistics were obtained and the data was expressed as mean ± SD, confidence intervals (CIs) (95%). The test-retest reliability (intraclass correlation coefficient [ICC]), within and between observers was analyzed for the *dv*. Five trials (5 digitized by the researcher, and the other 5 digitized by other researchers with experience in the processing computational routine), were conducted on 10 swimmers who completed 4 trials with different loads. The intraobserver ICC ranged between 0.95 (95% CI, 0.92 – 0.99) and 0.96 (95%, 0.92-0.98), and the interobserver ICC ranged from 0.97 (95% CI, 0.96 – 0.98) to 0.99 (95% CI, 0.98 – 0.99) for the tethered measurements.

The effect sizes (d) of the obtained differences were calculated and categorized (small if 0 ≤ |d| ≤ 0.5, medium if 0.5 < |d| ≤ 0.8, and large if |d| > 0.8 (Cohen, 1988). After Shapiro-Wilk testing for normality distribution, repeated measures 1-way ANOVA tests were carried out to find differences between the variables at 15, 30, 45 and 60% of the maximal load (ML). To detect differences between variables, significance was accepted at the alpha ≤ 0.05 level, and paired comparisons were used in conjunction with Holm's Bonferroni method for controlling type 1 errors.

Pearson product-moment correlation coefficients (r) were used to verify the relationship between the swimming velocities and the different sorts of strength-based and velocity-based variables obtained on the dry-land arm-stroke strength test. All statistical procedures were performed using SPSS 21.0 (IBM Chicago, IL, USA).

RESULTS

Mean, SD, P – values and Effect sizes for all tested STLS variables are presented in Table 1. Most of the variables were adversely affected by the load pulled. The velocity of swimming was different ($F_{3,13}$ = 977.72, p = 0.000) and decreased along with the load pulled. In addition, the time to complete the ten arm-strokes ($F_{3,13}$ = 12.616, p = 0.000) and the distance covered ($F_{3,13}$ = 307.22, p = 0.000) was also affected because both variables were progressively lower when increasing the load. The power values were different depending on the load (Mean: $F_{3,13}$ = 20.345, p = 0.000; Peak: $F_{3,13}$ = 27.158, p = 0.000). The highest mean values were obtained at 45% ML (Power: 57.50 ± 10.94 W) (Figure 2), meanwhile the peaks were both found at some point between 30 and 45% ML. From that point onwards, the power values decreased (Table 1).

The values of Force, Acceleration, Impulse and ImpRel were different in every effort ($p < 0.05$). The highest values of force and impulse were obtained at 60% ML, while the highest values of Acceleration and ImpRel were acquired at 15% ML (Table 1). The *dv* values were different ($F_{3,17}$ = 12.142, P = 0.000), although *post-hoc* only revealed a significant increase at 60% ML ($p < 0.002$) in comparison with the rest of the efforts. Finally, no differences were detected in *dF* as a consequence of increasing the load ($F_{3,13}$ = 1.851, P = 0.188).

(Please insert Table 1 near here)

(Please insert Figure 2 near here)

The correlations between the velocity of swimming and the variables collected in dry-land conditions through the Smith Machine's device are shown in Table 2. Pearson's correlation coefficient detected a moderate to strong relationship between the RM and the Relative_RM of the swimmers and the mean velocity with no load ($r = 0.496$, $p = 0.050$; $r = 0.529$, $p = 0.035$; respectively). Regarding the velocity achieved in the different STLS efforts, the RM only correlated with some swimming velocities manifestations at 60% ML, meanwhile the Relative_RM achieved some correlations at 15 and 30% ML (Table 2). On the other hand, MPV and MPP reached strong and moderate correlations with the mean swimming velocity with no load ($r = 0.709$, $p = 0.002$; $r = 0.564$, $p = 0.023$; respectively). Furthermore, some other correlations were found between these variables with the maximum and minimum velocities achieved in the different STLS efforts (Table 2). The higher the velocity and power applied on the dry-land test, the higher the velocity of swimming, even at different loads. Finally, the IMP acquired on the arm-stroke dry-land exercise, reached a negative correlation with the velocity of swimming with no load ($r = -0.554$, $p = 0.026$) and some of the STLS efforts (Table 2). In this sense, high values of impulse in the dry-land exercise were associated with lower velocities of real swimming, especially with the maximum velocities achieved at 30, 45 and 60% ML ($p < 0.03$).

(Please insert Table 2 near here)

DISCUSSION

One of the purposes of our study was to present an updated protocol to assess semi-tethered swimming performance in front crawl. The power vs. load curves presented an inverted ‘U’ shape (Figure 1), similar to those obtained by previous authors (Dominguez-Castells, et al., 2013; Garcia-Ramos et al., 2016). Nevertheless, although the peak power output was achieved at some point between the 30% ML (67.21 ± 10.79 W) and 45% ML (71.38 ± 10.12 W) ($p = 0.137$), the higher value of mean power was found at 45% ML (Figure 1), and it corresponded to a swimming velocity of 0.95 ± 0.06 m/s. Those values were very similar to the ones obtained by Dominguez-Castells, et al. (2013) (66.49 ± 19.09 W), although they reported lower velocity values (0.75 ± 0.18 m/s). In addition, those results were achieved at a very similar load percentage (47% ML: 3.95 ± 0.79 kg), although in the present study, that load percentage corresponded to a larger load mass (45% ML: 6.00 ± 0.98 kg). The reasons to discuss it are two-fold; At first, it is important to consider that leg kicking was not restricted in our study and it obviously provides significant propulsion (Deschodt, Arsac, & Rouard, 1999; Morouço, Marinho, Izquierdo, et al., 2015). Moreover, it has been noted that leg kicking has a considerable influence on body-roll because it applies a torque on the hip that limits the hip rotation (Sanders and Psycharakis, 2009). Therefore, it may provide a higher stabilization in the development of the swimming movements (Psycharakis and Sanders, 2010). On the other hand, the resistance offered by the added mass may be higher underwater given the quadratic nature of the hydrodynamic drag (Marinho et al., 2009). In such case, the external work was higher not only because of the increases of the load, but also because of the drag offered by the dumbbell when accelerating (Dominguez-Castells, et al., 2013; Hollander et al., 1986).

By contrast, in the study of Johnson, et al. (1993), the resistance of the added mass was applied externally on a power rack, and the values were collected without inhibiting the leg actions. Such a method was more akin to what was applied in this study, however, the peak power output was slightly higher than the maximal values achieved in this study (80 ± 21 W vs. 71.38 ± 10.12 W) and the load eliciting that peak power was significantly superior (7.8 kg) than the range of loads found in our study (4.37 – 6.00 kg). Possibly, since Power was calculated in both studies as (Force · Distance) / Time, the differences would come from the procedure to obtain the Force value. In the study of Johnson, et al. (1993), it was calculated solely as the weight pulled by the swimmers, meanwhile in the present study, the Force values were determined according to Newton's second law ($F = m \cdot a$). Therefore, the values achieved at high loads might have been countered by the low acceleration achieved (Table 1), and therefore, this may have influenced the outcomes obtained in Power.

Furthermore, according to the force-velocity relationship of the skeletal muscle, the outcomes obtained in Force and Impulse could be expected (Table 1), indicating that at very high velocity contractions, it is not easy to accumulate high amounts of force and impulse values and once the resistance loads grow, the force and impulse needed to overcome them increases (Dopsaj, et al., 2001; Garcia-Ramos, et al., 2016; Keskinen, Tilli, & Komi, 1989). Considering that any increase in swimming velocity requires a proportional increase in the applied muscle force to sustain such velocity (Vorontsov, et al., 2011), this fact may reflect an augmented quantity of the propulsive movements conveyed per stroke at high loads, a key that might be of success for sprinters (N. Amaro, et al., 2014; Dopsaj, et al., 2001). However, the loss of velocity and acceleration, together with the reduction of the distance covered and the time in the 10 arm-strokes were not in line with the increases obtained in force and absolute impulse at high loads but in line with the reduction of the Impulse normalized to the load pulled (ImpRel). Therefore, if STLS does not produce any increase on the propulsive skills, but deterioration on them, it should be highly reconsidered when including in-water resisted swimming routines, as little or no benefit may be obtained from them.

In any case, coaches should be aware that the application of different loads in STLS may affect the subjects' performance differently. Lower power production at fast velocities and low loads might indicate a high resistive drag and a low swimming efficiency, meanwhile a low power production at heavy loads and low velocities might indicate deficits in the swimmers strength (Dopsaj, et al., 2001; Johnson, et al., 1993). For that reason, another aim of this study was to examine the intra-cycle velocity (*dv*) and force variation (*dF*) along with the increasing loads. The dv% and dF% represents a balance between propulsive and resistive forces. The higher the dv% and dF% the poorer the performance, as it represents a low-efficient application of the forces in the water (Barbosa et al., 2013). In our study, the highest dv% was obtained at the highest load and lowest velocity. In fact, the deepest variation in dv% was detected between 45 to 60% ML ($p < 0.001$), coinciding also with the loss of swimming power (Table 1). These results were expected. Sustaining high swim velocities is obviously hard while pulling heavy loads because the swimmer is unable to find the impulse needed to overcome the resistance in an unstable environment such as water. It implies increases in power and strength requirements of the muscles (e.g. with speed), which require stiffer tendons to produce optimal efficiency and the required power with a given muscle volume. The greater force generated by muscle is associated with the transmission of more stress through the tendon. Consequently, higher muscle requirements also produce higher fatigue and it may affect the swimming technique adversely (Cuenca-Fernandez, et al., 2018).

Morouco, et al. (2017) reported that swimmers with higher dv% would also present higher dF%. However, the dF% did not change along with the increase of the load (Figure 2), and actually, it seemed to be slightly reduced as a consequence of it. Possibly, as the time to complete the 10 arm-strokes was shorter at higher loads, it indicated that every arm-stroke was not only shorter, but also produced less propulsive impulse. This modification on the stroke patterns may be a consequence of the increased difficulty to transfer the force into the water at maximal or sub-maximal loads and would also be consistent with the results found in the present study for

ImpRel (Table 1). Nevertheless, previous studies have shown that semi-tethered swimmers may increase the coordination index by overlapping the arm strokes, and this effect may reduce the dF% (Dominguez-Castells and Arellano, 2012; Schnitzierl, Seifert, Ernwein, & Chollet, 2008; Seifert, Chollet, & Bardy, 2004). Unfortunately, that variable was not measured in this study and future research should provide more information about this issue, testing also if swimmers with a high dF% may benefit from STLS practice to reduce it.

The associations found between the dry-land variables and the velocity of swimming (Table 2), are not new as previous studies have shown considerable interest in this field (Crowe, et al., 1999; Dominguez-Castells, et al., 2013; Garrido, et al., 2010; Perez-Olea, et al., 2018; Ravé, et al., 2018). In the study of Johnson, et al. (1993), the RM achieved on the *bench press* exercise was correlated with the swimming velocity (r = 0.55), meanwhile in the study of Garrido, et al. (2010), a similar correlation was found (r = 0.58) compared with the load at 6RM. However, both authors pointed out that the nature of the selected exercise was possibly not specific enough to expect that improvements in strength would result in improved swimming performance. In contrast, Crowe, et al. (1999), obtained higher correlations (r = 0.65), between the RM obtained in *lat pull-down* (i.e. in a pulling exercise) and swimming performance measured in 50 meters. For that reason, despite RM being more related with maximum force than with explosive force, the associations between swimming velocity with the RM (r = 0.49) and Relative_RM (r = 0.52) were explored in this study through a pulling exercise, which would support the development of muscular strength in swimmers, as it appears to play an important role in the determination of maximal swim velocity.

Nevertheless, it is worthy of review that while the RM only showed moderate to strong correlations with V60 (r = 0.68) and Vmin60 (r = 0.52) (i.e. at higher loads), the Relative_RM, reached correlations with V15 (r = 0.52), Vmin15 (r = 0.52) and V30 (r = 0.54) (i.e. at lower loads). Since the fact that producing a high percentage of Relative_RM is the greater capacity of force due to lower body weight, the Relative_RM index may reflect with more accuracy the strength abilities of the swimmers (Cuenca-Fernández et al., 2015). Possibly, considering that higher swimming velocities were achieved at low loads (Table 1), the correlation with the Relative_RM index may also reflect that those swimmers presented a lower surface area and hydrodynamic drag than the average (Hollander, et al., 1986). At 60% ML, under a severe reduction of swimming velocity ($p < 0.000$) and consequently in the drag acting against the body (Marinho, et al., 2009), the RM of the swimmers was shown as a predictor to achieve and maintain a higher swimming velocity (Table 2). It may indicate that regardless of their strength abilities, the swimmers with a high value of Relative_RM may presumably offer less drag than the average and it would be more reliable than testing only the RM to predict real swimming performance. Moreover, it would offer a valid and different rationale arguing why studies testing performance in tethered swimming (i.e. with no drag acting against the body) have shown to be more related with the absolute force values rather than with the relative ones (normalized to body mass) (Morouco, et al., 2011).

On the other hand, as movement velocity has shown to be a predictor of loading intensity and strength capability in resistance training (Gonzalez-Badillo and Sanchez-Medina, 2010), different velocity-based perspectives have been carried out to link performance obtained in dry-land conditions with actual swimming. Morouco, et al. (2011), found correlations ($r = 0.68$) between MPP in *lat pull down* and velocity of swimming in 50m. Meanwhile, in the study of Dominguez-Castells, et al. (2013) the maximum power obtained on a dry-land arm-stroke exercise, was relatively similar to maximum swim power ($r = 0.91$), and both of these power values were related to swim velocity ($r = 0.85$, $r = 0.72$). On the other hand, Perez-Olea, et al. (2018) recently demonstrated that the mean velocity reached in a test of maximal number of *pull-ups* correlated with swimming velocity ($r = 0.88$), and the relative loss of velocity during the pull-up test accounted for 84% ($p < 0.001$) of 50m freestyle performance variance. Thus, those results were in agreement with the ones obtained in this study as two of the velocity-based variables, MPV and MPP, correlated with different velocities achieved at different STLS efforts

(Table 2). Meanwhile, the negative correlation obtained between IMP and swimming velocity indicated that for a given force in N, the lower the velocity of the arm-stroke, the higher the time spent to complete the movement. Therefore, considering that swimming is characterized by producing fast movements in a short period of time, especially when sprinting (Seifert, et al., 2004), velocity-based dry-land variables may constitute an effective approach to predict actual swimming performance.

The results of the present investigation have shown that STLS alters the swimming kinetics and kinematics. A reduction of the time spent per stroke is obtained due to loaded swimming and it seems not possible to achieve the higher requirements of force/impulse needed to overcome the high loads. Those alterations seem to be higher from 45% ML onwards, with greater increases in critical variables as dv% which indicated a high difficulty to maintain a constant speed in the water and a deep deterioration in performance. Therefore, STLS should be cautiously administered to include specific high-intensity force development programs, since its transfer to improve the biomechanical skills of the swimmers seems questionable. Regarding the results obtained in the dry-land test, the swimmers with higher index of relative strength may obtain better results in STLS at low loads and higher speed, although the ability to develop a high amount of absolute strength seems relevant for swimmers. Possibly, as the velocity obtained when pulling a low resistance in the STLS likely reflects the combined contribution of the propulsive skills and minimized body drag, the improvement in either of these components could result in improved swimming performance scores. In any case, swimming performances seem to be better predicted through dry-land exercises which allow the development of high speed and explosive movements, possibly because actual swimming movements are produced quickly and intensely in a short period of time.

This study presented some limitations, as the correlations presented here were obtained according to swimmers' upper limb strength; however, the semi-tethered encoder recordings might not just be from the arm action throughout the underwater stroke, but also from the leg action. On the other hand, although participants had one previous practice with the STLS device, it was possible not enough to get familiarized enough with it. Nevertheless, a simple adaptation of a system used to measure performance in dry-land conditions allowed us to measure performance in swimmers. Moreover, this system has shown to be sensitive in obtaining valuable information about intra-cyclic velocity or force variation, which could lead coaches to focus on improving swimmer's technique rather than increasing physical conditioning.

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DECLARATION OF INTEREST STATEMENT

No potential conflict of interest was reported by the authors.

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Results

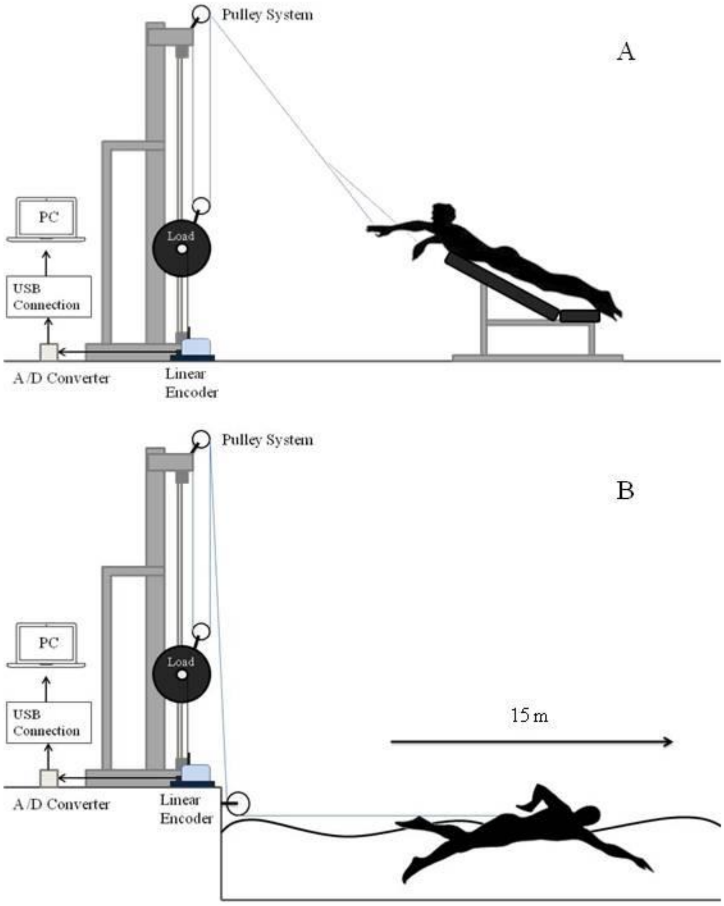
Table 1. Mean, SD and P – value for the variables obtained from the semi-tethered loaded swimming test at 15, 30, 45 and 60% of the maximal load (n=16). (*$P < 0.05$)

	Load 15%	*Versus*	Load 30%	*Versus*	Load 45%	*Versus*	Load 60%	
	Mean ± SD 95% CIs	P value (Post Hoc) Effect Size (95% CI)	Mean ± SD 95% CIs	P value (Post Hoc) Effect Size (95% CI)	Mean ± SD 95% CIs	P value (Post Hoc) Effect Size (95% CI)	Mean ± SD 95% CIs	P value (ANOVA)
Load Pulled (Kg)	2.31 ± 0.62 (1.97-2.64)	0.000 2.79 (1.41, 4.16)	4.37 ± 0.84 (3.92-4.82)	0.000 1.78 (0.62, 2.94)	6.00 ± 0.98 (5.47-6.52)	0.000 1.31 (0.23, 2.39)	7.37 ± 1.10 (6.78-7.96)	0.000*
DC10St (m)	14.10 ± 1.25 (13.43-14.77)	0.000 -1.93 (-3.12, -0.74)	11.59 ± 1.34 (10.88-12.31)	0.000 -2.03 (-3.24, -0.82)	8.59 ± 1.60 (7.74-9.45)	0.000 -1.49 (-2.60, -0.38)	6.72 ± 0.76 (6.31-7.13)	0.000*
T10St (s)	9.59 ± 0.84 (9.13-10.04)	1.0 -0.06 (-1.04, 0.91)	9.53 ± 1.01 (8.99-10.07)	0.736 -0.35 (-1.34, 0.63)	9.16 ± 1.07 (8.59-9.74)	0.029 -0.48 (-1.47, 0.51)	8.67 ± 0.95 (8.16-9.18)	0.000*
Velocity (m/s)	1.47 ± 0.06 (1.44-1.51)	0.000 -4.33 (-6.12, -2.54)	1.21 ± 0.06 (1.18-1.25)	0.000 -4.33 (-6.12, -2.54)	0.95 ± 0.06 (0.92-0.99)	0.000 -4.31 (-6.10, -2.52)	0.73 ± 0.04 (0.71-0.75)	0.000*
Force (N)	23.40 ± 6.48 (19.95-26.86)	0.000 3.19 (1.71, 4.67)	43.52 ± 8.54 (38.97-48.08)	0.000 1.77 (0.61, 2.92)	59.42 ± 9.38 (54.42-64.42)	0.000 1.28 (0.21, 2.36)	72.46 ± 10.83 (66.69-78.24)	0.000*
Acceleration (m/s^2)	0.30 ± 0.11 (0.24-0.36)	0.048 -0.85 (-1.88, 0.16)	0.21 ± 0.10 (0.15-0.27)	1.0 -0.21 (-1.19, 0.77)	0.19 ± 0.09 (0.14-0.24)	0.000 -0.99 (-2.03, 0.04)	0.11 ± 0.07 (0.07-0.15)	0.000*
Power (W)	34.34 ± 9.96 (29.03-39.65)	0.000 1.71 (0.57, 2.86)	52.44 ± 11.08 (46.53-58.35)	0.050 0.46 (-0.53, 1.45)	57.50 ± 10.94 (51.67-63.34)	0.000 -0.42 (-1.41, 0.56)	53.12 ± 9.81 (47.89-58.35)	0.000*
Peak Power (W)	49.24 ± 9.62 (50.73-63.81)	0.000 1.75 (0.60, 2.91)	67.21 ± 10.79 (62.16-80.36)	0.137 0.39 (-0.59, 1.38)	71.38 ± 10.12 (68.14-91.39)	0.000 -0.62 (-1.63, 0.37)	65.25 ± 9.44 (66.20-87.53)	0.000*
Impulse (N·s)	15.97 ± 3.55 (14.08-17.86)	0.001 1.62 (0.49, 2.75)	21.93 ± 3.78 (19.92-23.95)	0.004 1.11 (0.06, 2.17)	27.08 ± 5.30 (24.26-29.91)	0.011 0.41 (-0.57, 1.40)	29.50 ± 6.23 (26.18-32.82)	0.000*
ImpRel (N·s/Kg)	7.49 ± 2.82 (5.99-8.99)	0.008 -1.03 (-2.08, 0.00)	5.17 ± 1.42 (4.41-5.93)	0.292 -0.53 (-1.53, 0.45)	4.56 ± 0.74 (4.16-4.96)	0.009 -0.85 (-1.87, 0.17)	3.99 ± 0.59 (3.68-4.31)	0.001*
dv (%)	39.62 ± 10.75 (33.89-45.35)	1.0 0.39 (-0.59, 1.38)	43.56 ± 9.41 (38.54-48.57)	0.787 0.43 (-0.55, 1.42)	47.65 ± 9.38 (42.65-52.65)	0.000 1.15 (0.09, 2.21)	58.91 ± 10.13 (53.51-64.31)	0.000*
dF (%)	6.84 ± 1.68 (5.95-7.74)	1.0 0.33 (-0.54, 1.22)	6.40 ± 1.24 (5.74-7.07)	0.338 -0.25 (-1.13, 0.62)	5.83 ± 1.21 (5.19-6.48)	0.734 -0.18 (-1.06,0.69)	5.38 ± 1.72 (4.46-6.30)	0.188

Table 2. Pearson's correlation coefficients and P-value between velocity of swimming (Mean, maximum and minimum) obtained from the semi-tethered loaded swimming test (at 15, 30, 45 and 60% of the maximal load) and variables obtained through the dry-land arm-stroke test conducted on the Smith Machine's device; Maximal (RM) and relative dry-land load (Relative_RM); mean propulsive velocity (MPV), mean propulsive power (MPP) and; impulse (IMP) (n=16). *P < 0.05

		RM		Relative_RM		MPV		MPP		IMP	
	Mean ± SD	r	p	r	p	r	p	r	p	r	p
NoLoadV	1.75 ± 0.08	0.496	0.050*	0.529	0.035*	0.709	0.002*	0.564	0.023*	-0.554	0.026*
V15	1.47 ± 0.06	0.442	0.086	0.528	0.036*	0.664	0.005*	0.501	0.048*	-0.417	0.108
VMax15	1.97 ± 0.14	0.229	0.393	0.044	0.873	0.421	0.104	0.241	0.369	-0.468	0.067
VMin15	1.00 ± 0.15	0.300	0.258	0.520	0.039*	0.793	0.000*	0.279	0.296	0.105	0.699
V30	1.21 ± 0.06	0.364	0.165	0.426	0.100	0.344	0.192	0.711	0.002*	-0.585	0.017*
VMax30	1.76 ± 0.18	0.405	0.120	0.361	0.170	0.175	0.518	0.035	0.898	-0.612	0.012*
VMin30	0.64 ± 0.15	0.426	0.100	0.544	0.029*	0.163	0.546	0.314	0.236	0.103	0.703
V45	0.95 ± 0.06	0.451	0.079	0.366	0.163	0.665	0.005*	0.473	0.064	-0.472	0.065
VMax45	1.47 ± 0.18	0.400	0.125	0.427	0.099	0.502	0.047*	0.199	0.461	-0.678	0.004*
VMin45	0.42 ± 0.11	0.202	0.453	0.100	0.712	0.121	0.656	0.232	0.387	0.068	0.803
V60	0.73 ± 0.04	0.681	0.004*	0.438	0.090	0.506	0.046*	0.480	0.060	-0.410	0.115
VMax60	1.19 ± 0.15	0.362	0.169	0.474	0.064	0.429	0.097	0.190	0.481	-0.523	0.038*
VMin60	0.21 ± 0.06	0.522	0.038*	0.399	0.126	0.395	0.130	0.438	0.090	-0.144	0.595

Figure 1. Layout of the dry-land (A) and aquatic (B) protocols, designed to evaluate performance of the swimmers through the adaptation of a linear encoder.



Graphs

Figure 2. Average power/velocity/force vs. load curve (Above); Average intracyc velocity & force variation (dv/dF) vs. Maximum & minimum velocity values (Below), obtained from the semi-tethered loaded swimming test at 15, 30, 45 and 60% of the maximal load. The actual loads of that percentage corresponded to 2.31, 4.37, 6.00 and 7.37 kg, respectively (n=16). $^{*}P < 0.05$