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Research article

Front Crawl Swimming Performance and Bi-Lateral Force Asymmetry during Land-Based and Tethered Swimming Tests

Karini B. dos Santos [1]✉, Paulo C. Barauce Bento [1], Gleber Pereira [1], Carl Payton [2] and André L.F. Rodacki [1]
[1] Universidade Federal do Parana, R. Coracao de Maria, 92 – Jardim Botanico – Setor de Ciencias Biologicas – Curitiba, Parana, Brazil; [2] Manchester Metropolitan University, Crewe, United Kingdom

Abstract
The aims of this study were to investigate whether land-based and tethered swimming strength tests can explain swimming performance in 200-meter front crawl and, whether these tests were able to identify bilateral symmetry in force production. In the first session, eighteen swimmers completed a maximum effort 200 m front crawl swim (swimming performance) and 15 seconds maximal effort tethered front crawl swim. In the second session, participants performed the upper extremity isometric strength test. Peak force production of tethered swimming and isometric strength tests were significantly correlated for the strongest and weakest sides ($r = 0.58$ and $r = 0.63$, respectively; $p < 0.05$), but only peak force production during tethered swimming correlated with 200 m swimming performance time ($r = -0.55$, $p < 0.05$). Bilateral asymmetries in peak force and rate of force development were similar between the tethered swimming and isometric strength tests (peak force: 13%, $p = 0.24$; rate of force development: 15%, $p = 0.88$) However, both tests detected significant difference of peak force and rate of force development between body sides. The tethered swimming test can partially explain the 200 m front crawl swimming performance. In addition, the land-based and tethered swimming tests may be used to identify bilateral asymmetry of swimming.

Key words: isometric strength, swimmers, kinetics.

Introduction

Swimming performance is dependent upon swimmer's capacity to generate a high mechanical power output to overcome the hydrodynamic resistance from the water. An increase in swimming speed requires a corresponding increase in the applied muscle force, becoming clear that muscle strength is determinant of success in swimming performance (Formosa et al., 2011; Sharp et al., 1982). Most studies approaching the relationship between strength and swimming performance have focused on upper extremity strength and sprint performance, demonstrating a strong relationship (Loturco et al., 2016; Morouço et al., 2014; 2015a), whereas some have reported a much weaker association (Costill et al., 1986; Formosa et al., 2013). It is apparent from the literature that land-based strength measures may not be as closely associated to swimming performance as strength measures obtained during swimming or swimming-like activities (Vorontsov, 2011). In addition, different force measurement systems may present distinct results. For instance, 55% of variation in magnitude of active drag analyzed by the MAD system and assisted towing method may be explained by different swimming technique required in each system (Formosa et al., 2012).

In order to increase swimming performance, athletes have incorporated strength and power exercises into their training programs, much of which are performed on land-based exercises using swim bench and free weights. Despite requiring access to certain testing equipment (hardware and software), the measure of the swimmer's capacity to generate force is a very important practice (Loturco et al., 2016), being useful to monitor training progress and the efficacy of the swimmer's land- and water-based training programs (Vorontsov, 2011). Hence, the ability of swimmers to generate force has been assessed using land-based isometric and isokinetic tests, which are designed to determine the contribution of isolated muscle actions around a particular joint (e.g., shoulder girdle muscles). Isometric tests on land-based is associated with swimming performance (Loturco et al., 2016). In addition, it is used to establish the swimmers´ strength profile, clinically assess shoulder pain (McLaine et al., 2017) and monitor fatigue (Matthews et al., 2017). However, such tests may not fully reproduce the neuromuscular and biomechanical conditions involved in the stroke during swimming (Marinho and Júnior, 2004). In fact, more studies are needed to verify the correlation between isometric land-based test and swimming performance. In addition, the easy evaluation of the forces generated by a swimmer, under conditions that closely replicate the swimming demands (e.g. tethered swimming that involves multi-joint movements), is inevitably of interest and value to swimming coaches, sport scientists and other practitioners.

Tethered swimming is performed attaching a swimmer to an inelastic cable and the other end is connected to a load cell mounted on the end wall of the pool. This approach involves muscle activation patterns very similar to those observed in free swimming (Bollens et al., 1988) and it has excellent test-retest reliability (Nagle et al., 2016; Kjendlie and Thorsvald, 2006). Although arm stroke kinematics in free swimming may differ slightly from tethered swimming, in which the body does not displace relative to the water (Maglischo and Maglischo, 1984; Yeater et al., 1981) and may affect the force applied, tethered swimming has been considered a specific method to evaluate force in water (Dos Santos et al., 2013; Lee et al., 2014; Morouço et al., 2011; Santos et al., 2016). In addition, tethered swimming provides an attrac-

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tive possibility to quantify propulsive forces produced by each side of the body and, therefore, to determine asymmetries in propulsive forces. Thus, tethered swimming involves a more ecologically valid approach when compared to other testing methods evaluating in land-based tests (Dos Santos et al., 2013).

Swimming performance can be viewed as a function of the propulsive forces generated by the left and right sides of the body. Although similar contributions to propulsion might be anticipated from both body sides, a number of studies have shown differences in technique coordination (Barden et al., 2011; Chollet et al., 2000; Seifert et al., 2005a) and propulsive forces between left and right sides (Dos Santos et al., 2013). Dos Santos et al. (2013) reported that elite front crawl swimmers are more symmetrical than their sub-elite counterparts (13 N vs. 18 N of peak force difference between right and left sides in elite and sub-elite swimmers, respectively). It means that the elite swimmers present more similar propulsive forces between body sides when compared to their sub-elite counterparts. Thus, the ability of each side of the body to produce propulsive forces may be highly related to the capacity to generate large torques around the relevant joints. Some studies have showed a positive relationship between the force generated during land-based testing and swimming velocity in able-bodied (Hawley and Williams, 1991; Sharp et al., 1982) and disabled swimmers (Dingley et al., 2014). To date, no studies have determined whether differences in the ability to generate force with the left and right upper extremities in land-based strength test (using a maximal voluntary isometric contraction test) are related to propulsive force asymmetries measured during a tethered swimming.

Therefore, the aims of this study were to investigate whether land-based and tethered swimming strength tests can explain swimming performance in 200-meter front crawl and whether these tests were able to identify bilateral symmetry in force production. It was hypothesized that forces measured by land-based and tethered swimming tests would be correlated and these tests would also correlate with swimming performance and, that both tests (land-based strength and tethered swimming tests) would be able to identify possible asymmetries.

Methods

Participants

Eighteen male swimmers (age 21.3 ± 4.6 years; stature 1.77 ± 0.06 m; mass 69.6 ± 6.6 kg) of local competitive level (competitive experience greater than two years) provided informed consent to participate in the study which was approved by the University Ethics Committee. Their mean best 200 m freestye performance was 139.1 ± 8.3 s and training frequency was at least three times per week.

Procedures

The participants attended two sessions, separated by a minimum of one day and maximum of four days between them. They performed a maximal effort during 200 m front crawl swim and after resting, participants performed 15 seconds maximal effort tethered front crawl swim. The land-based isometric strength test was completed in other session. The order of these sessions was randomised.

A brief non-controlled low-intensity warm-up was performed for 10 minutes in a 25 m swimming pool with a water temperature of 29°C. Then, participants completed the 200 m swim with maximal effort. An experienced experimenter recorded the performance time manually. After a 30-minute recovery period (10 minutes of passive recovery and 20 minutes of active recovery) the maximum effort tethered swimming test was performed.

Kinematic and kinetic assessments of swimming

Kinematic measurements were obtained in the 200 m swim and the tethered swim, following the procedure described by Dos Santos et al. (2013). A digital camera (JVC GRDVL 9500, Japan) sampling at 60 Hz was positioned 10 m from the swimmer´s plane of the motion (above water). During the tethered swimming test, participants were approximately 3 m from the swimming pool end wall in the center lane. The free swimming was also performed in the center lane. The visual information from the camera and kinetic data were synchronized using a manually triggered pulse in the visual field of the camera and in one empty channel of the force measurements. This enabled key instants in the force-time traces, i.e. the beginning of the propulsive phase defined as the instant previous to the abrupt propulsive force increase, to be matched (qualitatively) with the swimming stroke instant in the video. The propulsive phase in the video was determined by the beginning of the hand's backwards movement in the water (Chollet et al., 2000). A calibrated strain gauge (Kratos, CZK 500, São Paulo, Brazil) was anchored to the wall end (out of the water) and attached to the swimmer's waist using an inextensible cable to provide the force-time traces. The force data were sampled at 500 Hz using an A/D converter (National Instruments, Model NI USB-6009). Based on residual analysis (Winter, 2009), data was filtered using a low-pass 2nd order Butterworth with cutoff frequency set at 15 Hz and stored in a personal computer using customized routine (Lab View Signal Express, version 3.0, National Instruments). A pilot study involving test-retest analysis confirmed the excellent reliability of the force measurements (ICC=.99), as it has been previously reported to tethered swimming assessments of competitive swimmers (Dos Santos et al., 2013; Kjendlie and Thorsvald, 2006).

Three consecutive stroke cycles were selected and the mean value of the measured parameters was calculated for analysis purposes. The stroke was defined as the instant of propulsive force increased abruptly until it reached its lowest point (Dos Santos et al., 2013). A customized routine (MATLAB 7.0) was used to calculate the force-time traces associated with these stroke cycles, for both the left and the right arm pull within each cycle: a) Peak force (Rupp et al.) -the largest horizontal component of the tether force, accounting for the angle of the tether cable with respect to the horizontal, and b) Rate of force development (RFD) - the gradient of the force-time curve between the periods that corresponded to 20% and 80% of the peak force, in each arm pull (Figure 1). Such percentage was chosen to guarantee that the RFD was calculated in a steep region of the force curve (Bento et al., 2010). The separate arm pulls were defined using the force-time traces from the instant the propulsive force increased abruptly until its lowest point, before initiating the pull of the opposite arm. The visual information from the camera was also used to confirm the onset of each arm pull. The tether cable angle was calculated using the known length of the tether cable and the height (anchoring point in the wall) with respect to the water level. The first 4 seconds of data from the tethered swimming were discarded to minimize possible changes in the cable tension and to allow the swimmer a time to establish a rhythm to their stroke.

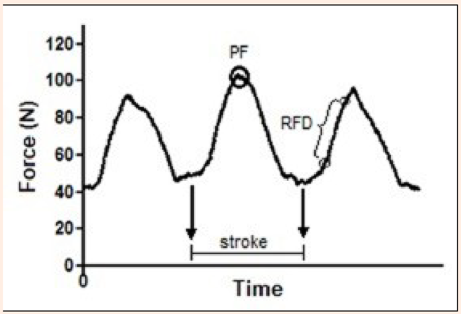

Figure 1. Typical force curve for a single stroke cycle (two arm pulls) in the tethered swimming test. PF = peak force; RFD = rate of force development.

The index of body side forces was calculated by the equation adapted from Robinson's symmetry index (Robinson et al., 1987):

$$SI = [S_{BS} - W_{BS}/0.5(S_{BS} + W_{BS})] \times 100$$

where, SI refers to the symmetry index, S_{BS} to the strongest body side and W_{BS} the weakest body side.

Land-based isometric strength test

The land-based strength test included only the upper limbs. During the test, participants were positioned in a prone posture on a bench with their elbow flexed approximately 90° and the thumb approximately in line with the externum bone when viewed in the sagittal pane (Figure 2). This position was taken to represent the middle of the propulsive phase of front crawl swimming. The hand of the assessed side was connected to a cable that was instrumented with the same strain gauge used in the tethered swimming test to enable the peak force and rate of force development to be determined. These two variables were quantified by the same procedure used in the analysis of the tethered swimming kinetic data. Three maximal effort trials were completed on each arm, with trials alternating between arms and with approximately 2-3 minutes rest between trials. For each arm, the trial with the greatest peak force was selected for analysis purposes. A trial was considered valid when the force-time data showed an abrupt and continuous increase until a relatively stable plateau was achieved during 3 seconds.

Figure 2. Schematic representation of the land-based maximal voluntary isometric test.

Statistical analysis

Initially, data normality and homogeneity were confirmed using the Shapiro-Wilk test and Levene test respectively. The peak force and rate of force development of tethered swimming and the land-based tests were correlated considering the strongest and the weakest sides of the body, using the Pearson correlation. The correlations between the tethered and land-based strength measures (mean of the left and right side values for peak force and rate of force development) with 200 m front crawl performance time were also calculated. A *t*- test for dependent measures was conducted to compare the weak and the strong sides in both land-based and tethered swimming tests. The statistics were calculated using Statistica (version 7, Statsoft Inc, USA) and the significance level was set at $p < 0.05$.

Results

In the tethered swimming test, peak force was the only variable that presented significant correlation with 200 m performance, accounting for approximately 30% of its variance ($r = 0.55$; $p < 0.05$). Figure 3 shows the relationships between peak force and 200 m performance, and rate of force development and 200 m performance.

A significant positive correlation was found between the peak force scores of tethered swimming and land-based strength tests, for both the strongest and the weakest side of the body ($r = 0.58$ and $r = 0.63$ respectively; $p < 0.05$). However, the rate of force development did not present a significant correlation between tests (Figure 4).

There were no asymmetry differences between the two tests, in which approximately 12% of asymmetry for the peak force in tethered swimming and 14% of asymmetry for land-based strength test ($t_{(18)} = 1.2$, $p > 0.5$); and approximately 15% of asymmetry for the rate of force development in both tests ($t_{(18)} = 0.16$, $p > 0.5$). However, both tests presented significant difference between the sides for peak force and rate of force development (Table 1). In addition, the symmetry indices of tethered swimming and land-based strength tests were 11% and 14% to the peak force, and 13% and 17% to rate of force development, respectively.

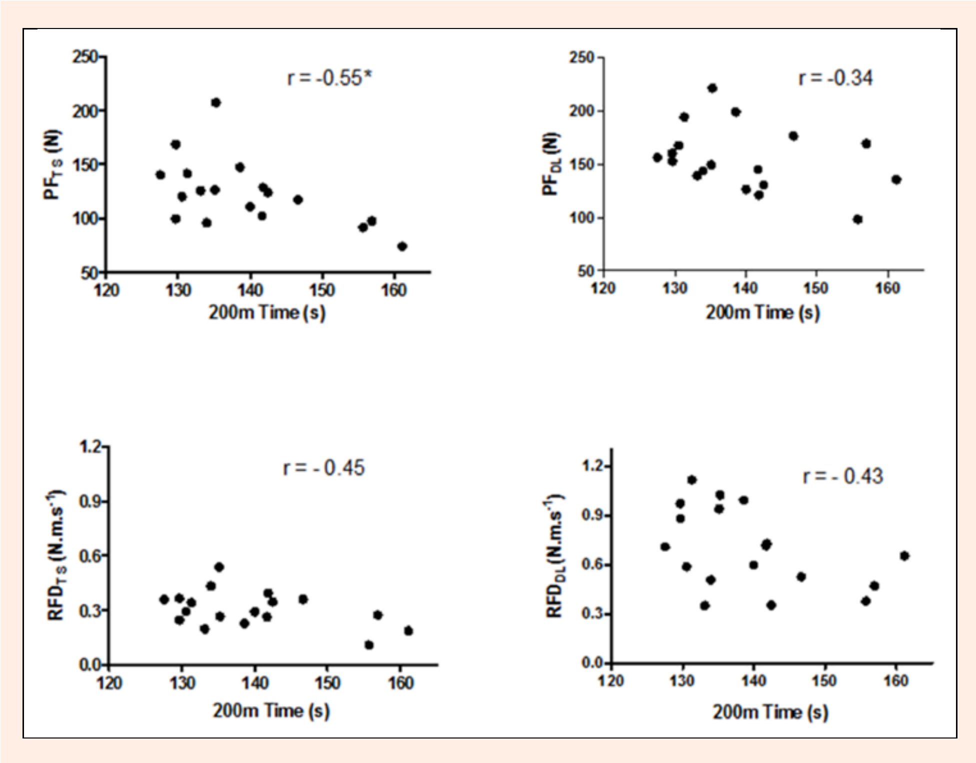

Figure 3. Correlation between peak force, (PF - upper panels) and rate of force development, (RFD - lower panels) with 200 m front crawl swimming performance for the tethered swimming test (left panels) and the land-based maximal voluntary isometric test (right panels) . * $p < 0.05$.

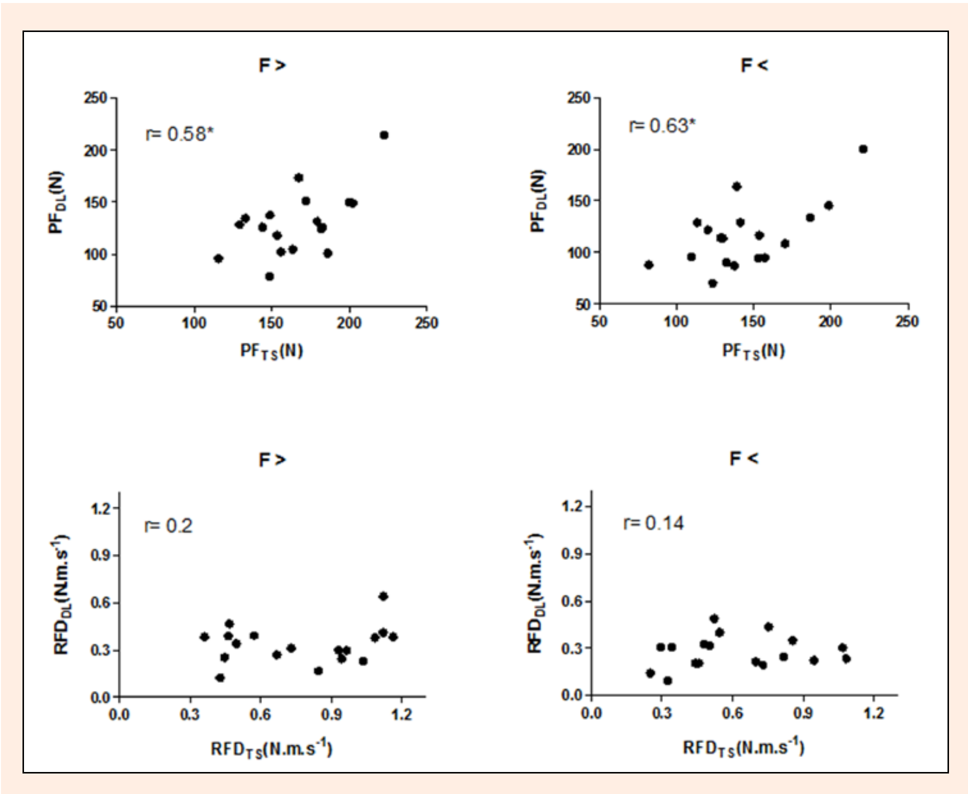

Figure 4. Correlation of the strongest side (F> left panels) and weakest side (F< right panels) of the body for the peak force, (PF - upper panels) and rate of force development, (RFD - lower panels) between tethered swimming (TS) and land-based maximal voluntary isometric test (LB). * $p < 0.05$.

Table 1. Peak force (PF) and rate of force development (RFD) (mean ± sd) for the strongest and weakest body sides in the tethered swimming and land-based maximal voluntary isometric tests.

	Tethered swimming (n = 18)					Land-based strength test (n = 18)				
	Strong	Weak	Mean	p	d	Strong	Weak	Mean	p	d
PF (N)	130.3	116.3	123.3	<.01	.46	165.6	144.1	154.8	<.01	.36
SD	±31.3	±31.4	±31.1			±58.2	±62.5	±60.1		
RFD ($N \cdot s^{-1}$)	330.5	276.4	303.4	<.05	.50	811.0	690.0	750.5	<.05	.34
SD	±114.5	±100.4	±107.4			±332.9	±394.5	±363.3		

"p" indicates significant differences between body sides; "d" refers to the Cohen's d coefficient for effect size.

Discussion

The main finding of this study was that only the peak force of tethered swimming test may partially explain 200 m front crawl swimming performance, although this variable was moderately correlated between tethered swimming and land-based strength tests. In addition, both tests were able to identify bilateral differences in force production.

Swimming training programs include resistance exercises on land-based as part of a competitive swimmer's usual routine. The use of these exercises is controversial since strength gained through land-based training does not equate to swimming-specific strength (Vorontsov, 2011) and consequently does not translate directly into performance improvements in the pool. For instance, Tanaka and colleagues (1993) did not find a swimming performance improvement after eight weeks of land-based resistance training (Tanaka et al., 1993). Therefore, the assessment of performance using land-based tests may also be questioned as the movements involved bear little resemblance to those used during swimming (Marinho and Júnior, 2004).

However, in the present study, the peak force of tethered swimming test accounted for 30% of 200 m front crawl swimming performance. As such a test requires an inexpensive device to measure the force during swimming, i.e. load cell, tethered swimming becomes an attractive strategy for coaches to monitor swimmer's capacity to generate force by checking training progress and the efficacy of land-based and water-based training programs.

The non-significant correlation of peak force and rate of force development between land-based strength test 200 m front crawl swimming performance confirms an important limitation of the isometric assessments in reproducing the dynamic conditions (e.g., stroke movements). Although the land-based strength test was designed to reproduce some characteristics of the swimming, it completely disregards the influence of the lower limbs that accounts approximately 30% of the propulsive forces and it plays a key role on performance (Morouço et al., 2015b).

Marinho and Junior (2004) also failed to establish a significant correlation between an isometric test (performed in a posture designed to replicate the upper limb position during the mid-sweep phase of front crawl swimming) and the maximum sprinting speed of a group of young swimmers of mixed performance level. Interestingly, a high correlation was found when the group was sub-divided into low performance ($r = 0.85$; $p < 0.05$) and high performance ($r = 0.22$; n.s.) groups, which indicated that less proficient swimmers rely more on force than on swimming technique. It also reinforces the premise that measuring high performance swimmers requires more specific testing, such as the tethered swimming test.

Although peak force during tethered swimming and the 200 m front crawl performance were correlated, the rate of development force did not relate to performance. The rate of force development reflects the ability to generate force rapidly and is believed to be one of the most important determinants of performance in sports that require high muscle power output (Jarić et al., 1989). The larger peak and rate of force development observed in land-based strength test in comparison to the tethered swimming can be explained by two factors. The first relates to the fact that higher peak forces are generally observed in isometric contractions when compared to concentric ones (Knudson, 2007). The second relates to the point of force application: in the isometric test, the forces were applied instantly to the load cell while in tethered swimming they were applied against a moving fluid and then transmitted through the body before being detected. This may have a dampening effect on the peak force and rate of force development in the tethered swim test. Irrespective of the influence of the measurements, the swimmers' rate of force development in the land-based strength test and in the tethered swimming test did not correlate with 200 m swimming performance.

In the present study, it was also aimed to establish whether bilateral force asymmetry could be detected in both tests (land-based strength test and tethered swimming), since it has been a relevant aspect to improve performance (Dos Santos et al., 2013) and to prevent shoulder injury (Olivier et al., 2008). The asymmetries found between sides were consistent in both tests, that is, the strongest side of the body was identified irrespective of the test and presented a small variation between test results (12-15% of difference between the strong and weak side to land-based and tethered swimming test, respectively). Although the land-based strength test is less specific than the tethered swimming, it may be used to identify upper limb asymmetries between body sides of swimmers.

Slight differences in force between sides are considered acceptable and inherent in the human body (Jaszczak, 2008). However, differences higher than 10% have been considered as functional asymmetries (Evershed et al., 2014; Formosa et al., 2014), which requires compensatory strategies (Evershed et al., 2014). For instance, Formosa et al. (2013 and 2014) showed symmetry for the coordination index with asymmetry for net force drag (Formosa et al., 2013; 2014). Asymmetries can be explained by motor control deficits (Chollet et al., 2000), dominance (Psycharakis and Sanders, 2008;

Tourny-Chollet et al., 2009) or factors associated with swimming technique, such as breathing, head position and asymmetry in body rolling (Seifert et al., 2008; Seifert et al., 2005b). Asymmetry investigations are important for guiding compensatory training that is aimed to avoid shoulder joint instability (Chollet et al., 2009), responding to excessive asymmetry (Seifert et al., 2005b) and providing a solid ground for force intervention planning, flexibility and technique to improve performance. The present study showed that swimmers asymmetry analysis can be assessed with both tethered swimming and isometric land-based tests, which involves relatively inexpensive devices.

Although it was asked to the swimmers to sustain the leg kicking during tests (200m front crawl and tethered swimming), the number of leg kicks were not controlled, which can be a limitation. Furthermore, land-bsased and tethered swimming tests were related only with 200 m front crawl performance, which represents a demand far greater than that applied in the tethered swimming, i.e. 15 seconds. Future studies including different distances or partial times are encouraged. In addition, underwater footage is indicated to include symmetry index calculation between arms.

Conclusions

The 200 m front crawl swimming performance can be partially explained by the tethered swimming test, whereas land-based test cannot. In addition, bilateral asymmetry of upper limbs in swimming can be identified through both land-based and tethered swimming tests.

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Key points

- The results of this study reinforce the notion that strength measured on land is a poor predictor of the swimming performance
- In contrast, the ability to generate maximum force during a tethered swim, a condition more analagous to free swimming, is a significant predictor of swimming performance.
- It is therefore recommended that simple land- and water-based strength tests, as described in this study, can be routinely used to monitor swimmers' asymmetry strength status.

AUTHOR BIOGRAPHY

Karini B. dos SANTOS
Employment
Professor, University Center Autonomous of Brazil
Degree
PhD
Research interests
Performance in swimming, kinetic and kinematic of swimmers
E-mail: kariniborges2@gmail.com

Paulo C. B. BENTO
Employment
Professor, Federal University of Parana. Department of Physical Education, Brazil
Degree
PhD
Research interests
Biomechanics, elderly, swimming
E-mail: p.bento063@gmail.com

Gleber PEREIRA
Employment
Professor, Federal University of Parana. Department of Physical Education, Brazil
Degree
PhD
Research interests
Biomechanics, elderly, endurance performance
E-mail: gleber.pereira@gmail.com

Carl PAYTON
Employment
Senior Enterprise Fellow in Biomechanics. Department of Exercise & Sport Science. Manchester Metropolitan University, Cheshire
Degree
PhD
Research interests
Biomechanics, performance, Paralympic swimming
E-mail: c.payton@mmu.ac.uk

André L. F. RODACKI
Employment
Professor, Federal University of Parana. Department of Physical Education, Brazil
Degree
PhD
Research interests
Biomechanics, elderly, performance, sports
E-mail: rodacki@ufpr.br

✉ **Karini Borges dos Santos**
Universidade Federal do Parana, R. Coracao de Maria, 92 – Jardim Botanico – Setor de Ciencias Biologicas – Curitiba, Parana, Brazil