A Correlational Analysis of Tethered Swimming, Swim Sprint Performance and Dry-land Power Assessments

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Abstract
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Swimmers are often tested on both dry-land and in swimming exercises. The aim of this study was to test the relationships between dry-land, tethered force-time curve parameters and swimming performances in distances up to 200 m. 10 young male high-level swimmers were assessed using the maximal isometric bench-press and quarter-squat, mean propulsive power in jump-squat, squat and countermovement jumps (dry-land assessments), peak force, average force, rate of force development (RFD) and impulse (tethered swimming) and swimming times. Pearson product-moment correlations were calculated among the variables. Peak force and average force were very largely correlated with the 50- and 100-m swimming performances ($r=-0.82$ and -0.74, respectively). Average force was very-largely/largely correlated with the 50- and 100-m performances ($r=-0.85$ and -0.67, respectively). RFD and impulse were very-largely correlated with the 50-m time ($r=-0.72$ and -0.76, respectively). Tethered swimming parameters were largely correlated ($r=0.65$ to 0.72) with mean propulsive power in jump-squat, squat-jump and countermovement jumps. Finally, mean propulsive power in jump-squat was largely correlated ($r=-0.70$) with 50-m performance. Due to the significant correlations between dry-land assessments and tethered/actual swimming, coaches are encouraged to implement strategies able to increase leg power in sprint swimmers.

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Introduction
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Swimming sprinting is highly influenced by a wide range of neuromuscular and biomechanical factors, such as muscle power, propelling efficiency and mechanical work [40,55]. Although these neuromechanical capacities play an important role in swimmers' performance, the assessment of force-time curve parameters in aquatic environments is not simple. For such purposes, researchers and coaches have been widely using tethered swimming to measure/quantify the net forces throughout the stroke cycle, due to its specificity and sensitivity on monitoring swimming training adaptations, without significant changes in stroke and physiological responses compared to free-swimming [17,41]. For instance, it has recently been shown that peak force in tethered swimming is moderately correlated ($r=0.61$) with 200-m crawl swimming performance [48]. Higher correlations are expected when shorter distances are used, as neuromuscular abilities (i.e., maximum muscle strength

and power) predominate over aerobic endurance. In fact, this correlation increases to 0.91 in 50-m crawl swimming [41].

To improve strength and power, top-level swimmers commonly execute traditional strength-exercises (i.e., bench press and squat) on dry-land [40]. It is assumed by some practitioners that the training adaptations resulting from these non-specific strategies are able to enhance swimming performance [6,19]. Therefore, it is interesting to ascertain which dry-land testing and training methods provide results more closely related to performance in tethered and actual swimming. This would help coaches to choose the most effective, suitable and practical training strategies and exercises capable of eliciting adaptations with positive transference to swimming kinematic and dynamic characteristics. For instance, mean propulsive power in the squat exercise and the total work during the countermovement jump (CMJ) presented high correlations with the average swimming force in tethered swimming ($r=0.73$ and 0.75, for squat

and CMJ, respectively) [42]. However, the relationship between the maximum strength capacity and the force-time curve parameters assessed by tethered swimming remains to be established. Since the force production is directly related to the mechanical work, it is expected that stronger swimmers will be able to present higher outcomes in the tethered force parameters collected in tethered swimming and in the actual swimming performance in distances ranging from 50- to 200-m (assuming similar kinematics across individuals).

The first aim of this study was therefore to test, in a sample composed of high-level young swimmers, the relationships between tethered force-time curve parameters and actual swimming performances for distances of 50, 100 and 200-m. The second aim was to determine the exercises and the mechanical variables more closely related to tethered force-time curve parameters. Finally, the correlations between dry-land tests (strength-power exercises regularly performed by the investigated participants during their training routines) and specific swimming performance were investigated. Since the significant relationships between strength and power measurements and specific performance in a wide range of sports disciplines have been extensively reported [7, 8, 14, 30, 32], even in an aquatic environment, we expected that stronger and more powerful athletes would perform better in specific and tethered swimming tests.

Methods
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Experimental design
This study aimed to quantify the relationship between dry-land and specific swimming assessments of neuromuscular function in highly trained swimmers. The dry-land tests/exercises were chosen in conjunction with the technical staff, according to the training routine of the swimmers, who regularly perform the following multi-joint exercises during their strength-power sessions: plyometrics (vertical jumps), bench-press, jump squats and quarter-squats. Therefore, these tests are always included in the assessment battery of these high-level athletes, frequently evaluated in our laboratory. Swimming performance and tethered propulsive force were tested in a 25-m pool (water temperature = 27 °C) during the competitive period of the second macrocycle of the year, using only the front-crawl technique. Tests were preceded by a standardized warm-up, which consisted of 1 000 m of low-to-moderate intensity in front crawl swimming (subjectively determined by the swimmers). Swimming performance was recorded as the time to complete 50, 100, and 200-m, respectively, at maximal speed. In the tethered swimming, peak force, average force, impulse and rate of force development were recorded. All variables collected during the assessments were used to test the correlations between dry-land, tethered and actual swimming performance. Although correlations do not imply cause and effect, this analysis could be important to determine the most adequate/effective exercise to improve swimming sprinting performance.

On all occasions, swimmers attended the test sessions after resting for at least 24 h, during which time they were asked to avoid strenuous exercise. In addition, they were instructed not to consume caffeinated and alcoholic beverages during the same period to avoid interfering with the tests results.

Subjects
10 well-trained male swimmers (age: 17.0 ± 0.7 years, height: 1.77 ± 0.05 m, body mass: 70.4 ± 6.3 kg, training experience: 7.5 ± 2.2 years) took part in this study after being informed of the potential benefits and hazards associated with participation. All the participants had reached the official cut time for National Championship participation, while 8 of the 10 ended the season ranked in the top 10 in the country, attesting to their high competitive level. The study procedures were approved by a local ethics committee, and the participants and their legal guardians (if under age 18) signed an informed consent form prior to study commencement; participants were free to withdraw at any time without penalty. The current investigation also adhered to standards of the International Journal of Sports Medicine described by Harriss and Atkinson [23].

Propulsive force in tethered swimming
Propulsive force was evaluated by means of a fully tethered swimming system (CEFISE, Nova Odessa, Brazil). The athletes were familiar with the test as it had been performed during their training sessions with the aim of monitoring training responses. The tethered system consisted of a load cell with 4 strain gauges and 2 000 N of maximum capacity. One end was attached to a specially designed support, fixed to the starting block, while the other was connected to a cable system with negligible extensibility (composed of a 10 mm caliber braided polypropylene rope with a rupture point of 751 000 N and a deformation rate of approximately 0.003 mm/N), to which the swimmer was tethered at the waist through an adjustable belt. Deformations in the load cell generated by swimmers' efforts during testing procedures were recognized by an A/D interface and stored at 200 Hz. The test consisted of two 10-s maximal swims, with a 4-min passive rest between trials to prevent fatigue, at a self-selected stroke rate. The start (after 8 strokes at moderate intensity) and end of the test protocol were signaled by a whistle and 1 s was given between the whistle and the start of data acquisition to avoid inertial effects, as adopted previously [9]. Swimmers were requested to hold their breath to avoid major modifications of stroke kinematics [20]. Individual force-time curves were smoothed using a fourth-order Butterworth low-pass digital filter with a cut-off frequency of 10 Hz, defined by the use of residual analysis [61]. In each trial, the main points shown in ○ **Fig. 1** were marked in 14 consecutive complete cycles (i.e., the interval between 2 successive lowest points) for the assessment of:

1) *Peak force (F_{PEAK}, expressed in N)*: the highest force value between 2 consecutive minimum force values (ICC = 0.95, CI 95 % = 0.82–0.99, p < 0.0001; CV = 1.7 %, CI 95 % = 0.4–3.0 %);
2) *Average force (F_{AVG}, expressed in N)*: the average of all force values between 2 consecutive minimum force values (ICC = 0.98, CI 95 % = 0.93–1.00, p < 0.0001; CV = 1.8 %, CI 95 % = 0.7–2.9 %);
3) *Impulse (IMP, expressed in N·s)*: the force applied in a given time. In this case, the area under the force-time curve between 2 successive minimum force values (ICC = 0.97, CI 95 % = 0.88–0.99, p < 0.0001; CV = 1.8 %, CI 95 % = 1.0–2.7 %);
4) *Rate of force development (RFD, expressed in $N \cdot s^{-1}$)*: ratio between force variation (ΔF = peak force minus its previous minimum force value) and time variation (Δt = time when peak force was reached minus time at its previous minimum force value), according to: $RFD = (\Delta F / \Delta t)$ (ICC = 0.72, CI 95 % = 0.20–0.92, p = 0.007; CV = 6.9 %, IC 95 % = 3.1–10.8 %).

This analysis was repeated for the 2 efforts performed and the average value was retained for analysis.

Actual swimming performance

Each swimmer performed maximal front-crawl swims of 50-, 100- and 200-m with a diving start, on the same day, 45 min apart (active recovery was allowed). The trials were manually timed by an experienced operator using a chronometer.

Isometric strength assessment

The maximal isometric strength was determined for the upper and lower limbs through bench press (BP) and quarter-squat (QS) exercises, both performed on a Smith-machine (Hammer Strength Equipment, Rosemont, IL, USA). Before performing the tests, the athletes completed a 20-min standardized warm-up, including 15-min of general (i.e., 10-min running at a moderate pace followed by 5-min of lower-limb active stretching) and 5-min of specific exercises (i.e., submaximal attempts at quarter-squat and bench press exercises). The QS were executed in a "quarter position" since this position is more similar to the positions/movements utilized by swimmers during actual swimming (i.e., block start, flutter kicks, flip turn, etc.) [3,5,47]. The knee angle used for each athlete was ≈ 135°, with the intention of maximizing peak force in the quarter squat, as previously reported [11,57]. For BP, the barbell was positioned across the swimmers' chest, at the level of their nipples. The athletes held the barbell at shoulder width, with an initial elbow angle of ≈ 90° [53] (angle between the arm and the forearm). For both measurements, after a starting command, the subjects exerted force as rapidly as possible against a mechanically fixed bar, for 5 s. The peak forces (PF) were determined using a force platform with custom designed software (AccuPower, AMTI, Graz, Austria), which sampled at a rate of 400 Hz [58]. The platform was fixed to the floor using a specific base. For BP testing, a bench was fixed to the platform and the force applied against the barbell was transmitted by the bench to the force platform in the vertical plane. Rate of force development (RFD) was determined as the average slope of the force-time curve (Δ Force/Δ time), for the first 100 ms, after the onset of the muscle contraction. Strong verbal encouragement was provided during the attempts.

Mean propulsive power

Mean propulsive power (MPP) was measured in the jump squat and bench press exercises, both being executed on a Smith-machine (Hammer Strength Equipment, Rosemont, IL, USA). The athletes were instructed to execute 3 repetitions at maximal velocity for each load, with a 5-min interval provided between sets. The load started at 40% of individual body mass in the jump squat (JS) and 30% in the bench press. A load of 10% of body mass for JS and 5% of body mass for BP was gradually added in each set until a decrease in mean propulsive power was observed. In the JS, the swimmers executed a knee flexion until the thigh was parallel to the ground and, after a verbal command, jumped as fast as possible without their shoulder losing contact with the barbell. During the BP, the athletes were instructed to lower the bar in a controlled manner until the barbell lightly touched their chest and then move the bar as fast as possible. To determine MPP, a linear transducer (T-Force, Dynamic Measurement System; Ergotech Consulting S.L., Murcia, Spain) was attached to the Smith-machine bar. The bar position data were sampled at 1 000 Hz using a computer. Finite differentiation technique was used to calculate bar velocity and acceleration. MPP rather than peak power in both jump squat and bench press was used since Sanchez-Medina et al. [46] demonstrated that these mean mechanical outputs during the propulsive phase better reflect the differences in the neuromuscular potential between 2 given individuals. The maximum MPP value obtained in each exercise was obtained for data analysis purposes.

Vertical jumping ability

Vertical jumping ability was assessed through squat and countermovement jumps (SJ and CMJ, respectively). The athletes performed 5 attempts, with a 15-s interval between each jump. In the SJ, a static position with a 90° knee-flexion angle was maintained for 2 s before a jump attempt without any preparatory movement. In the CMJ, swimmers were instructed to execute a downward movement followed by a complete extension of the legs. To avoid changes in the jumping coordination pattern, the amplitude of the countermovement was freely determined. All jumps were executed with the hands on the hips. The jumps were performed on a contact platform (Smart Jump; Fusion Sport, Coopers Plains, Australia) with the recorded flight time (t) being used to estimate the height (h) of the rise of the body's center of gravity during the vertical jump (i.e., $h = gt^2/8$, where $g = 9.81 \ \text{m} \cdot \text{s}^{-2}$). Any given jump would only be considered valid for analysis if the take-off and landing positions were visually similar. The best attempt was retained for data analysis.
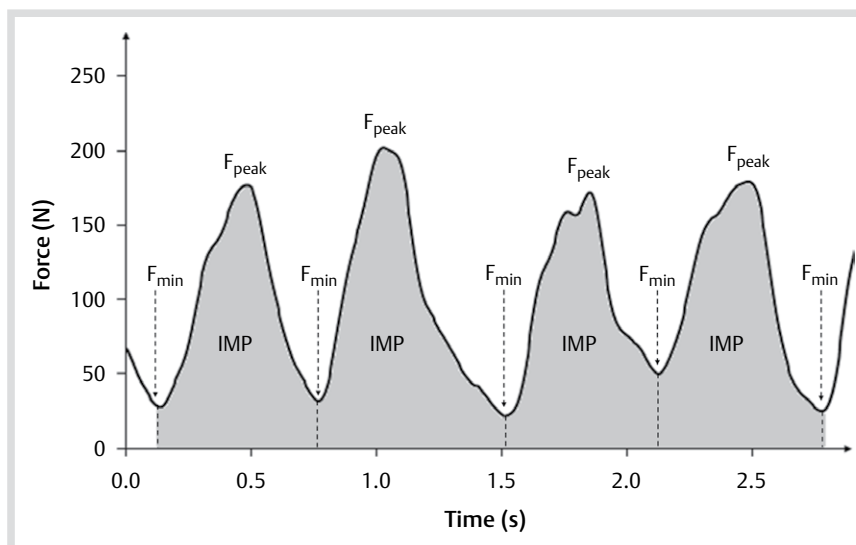

Fig. 1 Example of 4 consecutive cycles of a front-crawl curve and also the main points used for force-time curve analysis. F_{PEAK} = peak force; IMP = Impulse; F_{min} = minimum force.

Statistical analyses

Data were checked for normality using the Shapiro-Wilk test, and presented as mean, standard deviation and 95% confidence interval. The strength of the relationships between variables obtained in dry-land strength and power exercises, tethered and actual swimming performances were determined by Pearson product-moment correlations. The threshold used to qualitatively assess the correlations was based on Hopkins [24], using the following criteria: <0.1, trivial; 0.1–0.3, small; 0.3–0.5, moderate; 0.5–0.7, large; 0.7–0.9 very large, >0.9, nearly perfect. Intraclass correlations (ICCs) were used to indicate the relationship between vertical jumps (SJ and CMJ) and muscle power assessments (BP and JS) for height and mean propulsive power. The ICC was 0.96 for the SJ, 0.95 for the CMJ, 0.93 for the BP and 0.93 for the JS. The statistical significance level for all the analyses was set at $P < 0.05$.

Results
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Descriptive data of parameters obtained in dry-land exercises, tethered and front crawl swimming are presented in ◉ **Table 1**. The F_{PEAK} was very largely correlated with the 50- and 100-m swimming performances. The F_{AVG} was very largely and largely correlated with the 50- and 100-m performances. The RFD and IMP were very largely correlated only with the 50-m time (◉ **Table 2**).

The F_{AVG}, F_{PEAK}, IMP and RFD presented large to very large correlations with JS_{MPP}, SJ and CMJ (◉ **Fig. 2**). Correlations with isometric BP and QS parameters (peak force and rate of force development) were not significant.

The only dry-land variable significantly correlated with the actual performance in 50-m swimming was the jump squat mean propulsive power ($r = -0.70$, $P < 0.05$).

Discussion
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This is the first study to investigate the correlations between performance in actual swimming tests over different distances (50-, 100- and 200-m) and tethered swimming and also their relationships with selected dry-land test outcomes at the same time. The main findings presented in this paper are threefold: (1) on average, there were large to very large correlations between actual swimming performance (in 50- and in 100-m) and tethered swimming performance; (2) the variables collected in the lower limb power tests (in loaded and unloaded conditions) were largely to very largely related to the tethered swimming mechanical outputs; and (3) the JS_{MPP} partly explained the swimmers' performance in the 50-m freestyle ($r = 0.75$).

Other studies have reported correlations between tethered and actual swimming performance in short-distance events [38,41]. Indeed, tethered swimming is a reliable method to measure the mechanical outputs in aquatic environments, being extensively recognized as a powerful tool to assess the specific forces applied by swimmers during specific movements. From a mechanical point of view, it is expected that swimmers capable of applying higher amounts of force/power against the water and, therefore, generate higher propulsive forces in their specific setting, will perform better in swimming time trial tests [49]. Importantly, the time-dependent variables derived from the tethered assessments (RFD and IMP) are solely related to 50-m swimming times ($r = -0.72$ and 0.76, for RFD and IMP, respectively). It is likely that the ability to rapidly develop muscular force (i.e., slope of force time curve = RFD) [1,4] and the force-time product [1] (i.e., impulse) in the water heavily influence only the swimmers' performance over very-short distances, whereas over longer distances other factors related to aerobic endurance and efficiency may weaken the relationship between explosive power and swimming performance [12]. This is related to the test duration (10-s) in tethered swimming. Seen from a technical perspective, the fast movements that occur during a 50-m front crawl swim depend directly on the muscles' capacity to contract rapidly and, consequently, on the neuromuscular measures related to the time [1]. The absence of strong relationships between tethered swimming parameters and the 200-m swim times may be explained by the metabolic and physiological factors that determine performance at this distance along with the duration of the current tethered swimming test. For instance, the intensity of maximal oxygen consumption and critical force (fatigue threshold as derived from the force-time relationship) [37] measured in the tethered protocol presented very large correlations with the 200-m performance ($r = 0.89$ and 0.63, respectively) in a recent study [45].

Performance in explosive vertical jumps is highly associated with neuromechanical capacities (i.e., muscle strength and
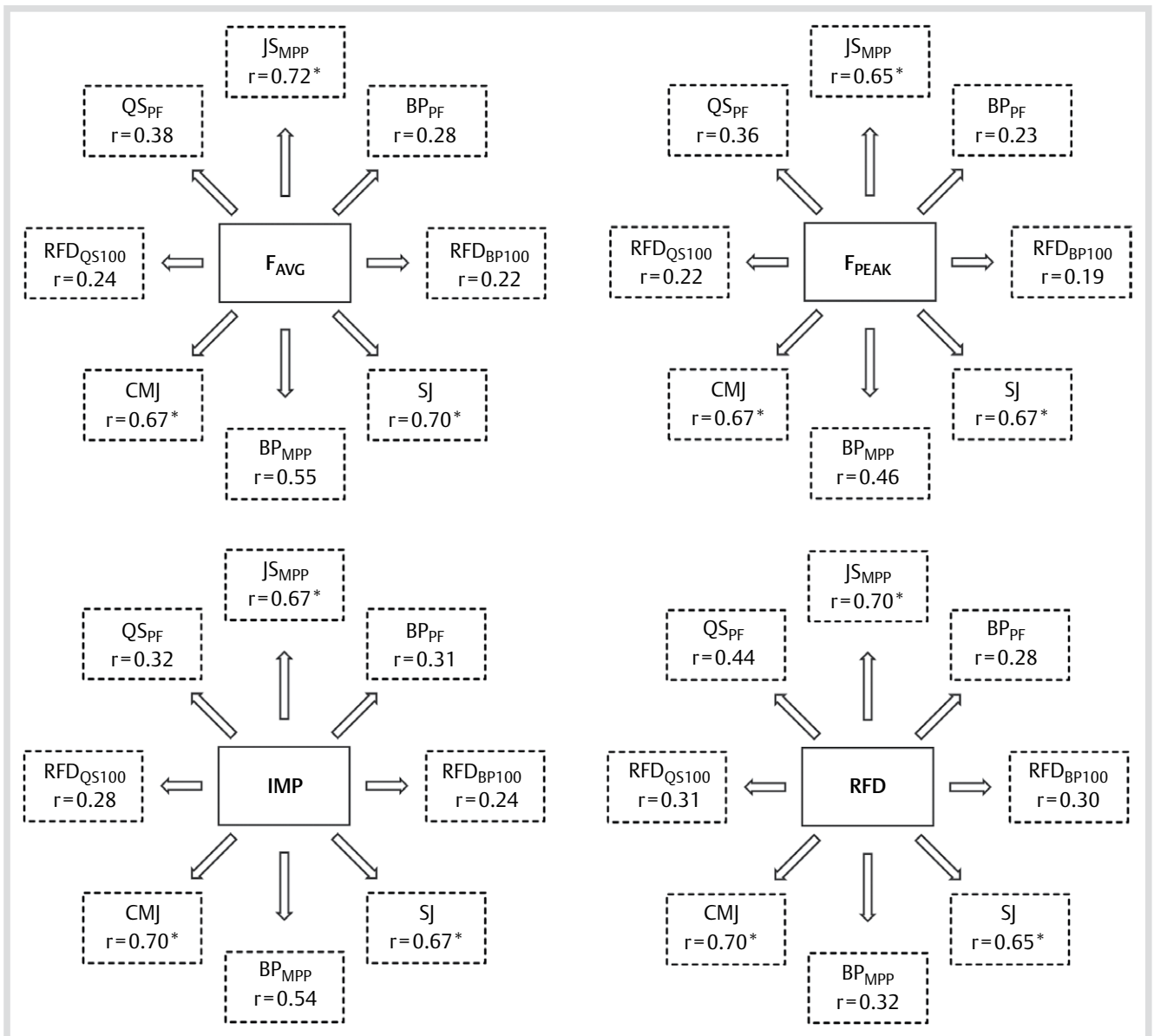
Table 1 Descriptive analysis (mean, standard deviation [SD] and 95% confidence interval [CI]) of front crawl swimming, tethered swimming and dry-land variables.

Swimming performance	Mean ± SD	CI (95%)	
		Lower	Upper
Time 50 (s)	25.02 ± 1.13	24.21	25.83
Time 100 (s)	54.49 ± 2.47	52.72	56.25
Time 200 (s)	123.03 ± 7.64	117.56	128.49
Tethered swim variables			
F_{PEAK} (N)	207.1 ± 27.2	187.6	226.6
F_{AVG} (N)	133.2 ± 16.8	121.2	145.3
RFD (N·s^{-1})	472.0 ± 77.6	416.3	527.6
IMP (N·s)	77.3 ± 8.1	71.4	83.1
Dry-land variables			
SJ (cm)	37.53 ± 6.51	32.87	42.19
CMJ (cm)	41.29 ± 6.27	36.79	45.78
JS_{MPP} (W)	577.60 ± 124.09	488.82	666.37
BP_{MPP} (W)	395.40 ± 50.54	359.24	431.55
QS_{PF} (N)	1168.80 ± 109.26	1090.63	1246.96
BP_{PF} (N)	2062.30 ± 315.33	1836.62	2287.87
RFD_{QS100} (N·s^{-1})	6598.02 ± 1327.90	5648.04	7547.91
RFD_{BP100} (N·s^{-1})	5686.04 ± 1554.31	4574.10	6797.80

F_{AVG} = Average Force; F_{PEAK} = Peak Force, IMP = Impulse; RFD = Rate of Force Development; JS_{MPP} = Mean Propulsive Power in Jump Squat; BP_{MPP} = Mean Propulsive Power in Bench Press; QS_{PF} = Peak Force in Quarter Squat; BP_{PF} = Peak Force in Bench Press; RFD_{QS100} = Rate of Force Development in 100 ms in Squat; RFD_{BP100} = Rate of Force Development in 100 ms in Bench Press; SJ = Squat Jump; CMJ = Countermovement Jump

Table 2 Correlations between tethered swimming variables and 50-, 100-, and 200-m actual swimming performances.

	50-m	100-m	200-m
F_{PEAK}	−0.82**	−0.74**	−0.35
F_{AVG}	−0.85**	−0.67*	−0.18
RFD	−0.72**	−0.61	−0.33
IMP	−0.76**	−0.51	−0.05

*$P < 0.05$; **$P < 0.01$

Fig. 2 Correlations between tethered swimming variables and dry-land neuromuscular tests * *P*<0.05. F_{AVG} = Average Force; F_{PEAK} = Peak Force, IMP = Impulse; RFD = Rate of Force Development; JS_{MPP} = Mean Propulsive Power in Jump Squat; BP_{MPP} = Mean Propulsive Power in Bench Press; QS_{PF} = Peak Force in Quarter Squat; BP_{PF} = Peak Force in Bench Press; RFD_{QS100} = Rate of Force Development in 100 ms in Squat; RFD_{BP100} = Rate of Force Development in 100 ms in Bench Press; SJ = Squat Jump; CMJ = Countermovement Jump.

power) [30, 31]. Although a previous study has already reported significant relationships between lower limb power (assessed in the squat exercise) and the variables of force collected in tethered swimming [38] (*r*≈0.65), the data reported herein are the first to investigate these correlations using vertical jumps in loaded (jump squats) and unloaded conditions (SJ and CMJ), simultaneously. More generally, the significant correlations (*r*≈0.70) between direct/indirect leg power measurements (mean propulsive power for JS, and height for CMJ and SJ) and tethered swimming outputs (RFD, IMP, F_{AVG}, and F_{PEAK}) presented in this study might be elucidated by analyzing the isolated influence of the limbs on the tether forces applied during the front crawl swim. Actually, the "flutter leg-kick" not only contributes significantly to tether force in the crawl stroke, but also produces higher values of force than the arms alone [62], which may largely affect the result of the swimmers' propulsion. It is also noteworthy that the use of the leg kick greatly contrib-

utes to reducing trunk inclination (≈12.7%) [21] and, according to the hydrodynamic theory [54], this is a factor that may meaningfully diminish the total amount of the resistive drag forces that need to be overcome by the swimmer. It is then conceivable that swimmers with higher dry-land lower-limb power levels also have a greater ability to keep their body in a more horizontal position in the water, and, consequently, to achieve a greater swimming speed. From an applied perspective, the possible relationships between JS, SJ and CMJ and flutter kick and the technical improvements – which may be attained by applying higher levels of leg power (i.e., keeping the body in a more horizontal position) – might plausibly explain the moderate/strong associations between lower limb muscle power and tethered forces.

On the other hand, contrary to previously reported data [26, 39], our results indicated that the bench press mean propulsive power was unable to explain any mechanical measure of the

tethered swimming, limiting the role of the upper limbs in generating forces to propel the athletes during these tests. However, this finding must be viewed with caution, since our variables were collected using an "extension/pushing exercise" (i.e., bench press). It is conceivable that pulling exercises (i.e., bench pull and pull down exercises) better mimic the movements executed by swimmers' in tethered conditions, being more associated with the mechanical outputs [16] resulting from these tests.

The multi-joint isometric tests are considered reliable and valid methods to evaluate functional muscle strength [56,60] capacity and RFD, since they possess strong to very strong correlations with maximal dynamic measurements (i.e., 1-RM tests) [10,36]. It is important to emphasize that, even in dynamic conditions, the maximal strength assessments are executed at very low velocities, which is quite different from the fast velocities presented by sprint swimmers when performing specific crawl movements [13], during actual or tethered swimming tests [18]. These kinematic differences possibly explain the lack of significant relationships between the isometric measures (BP_{PF} and RFD, and QS_{PF} and RFD) and all variables assessed in the actual or tethered swimming presented here. This finding is in line with a number of studies which have argued that the parametric relationship between force and velocity (i.e., the higher the load, the lower the velocity) plays a crucial role in modulating the neuromuscular adaptations induced by a strength training regimen [2,14,15]. Several studies have suggested that training with heavy-loads results in greater improvements in the high-force/low-velocity part of the force-velocity curve, whereas light-load training methods provoke superior increases towards the high-velocity/low-force end of the curve [25,27,28]. Although in this cross-sectional study we did not investigate the neuromechanical adaptations caused by a strength-training period, it is reasonable to assume that these kinematic factors affect the relationships between "fast-swimming-movements" and the amount of force applied in maximal strength tests [14]. Importantly, future studies should be designed to test this assumption. Jump squats are widely used by coaches to improve the lower limb muscle power of elite athletes [43,44]. Indeed, there is extensive literature attesting the effectiveness of this exercise in enhancing specific sport performance [43,44]. However, most of these studies were conducted using subjects from dry-land sport specialties, which hamper their application in aquatic environments [52]. We found only 4 studies [29,39,50,51] that investigated the correlations between swimming velocity and leg power assessments executed in dry-land settings. Although the results were not conclusive, the authors used exclusively vertical jumps in unloaded conditions (i.e., CMJ) or strength-exercises without jumping (i.e., half-squats) in their analyses. To our knowledge, this is the first investigation to examine the relationships between the mean propulsive power collected during loaded vertical jumps (i.e., jump squats) and swim sprint performance in male high-level swimmers. Notably, our results indicate a strong correlation ($r=-0.75$) between JS_{MPP} and 50-m swim times, suggesting that this exercise may significantly influence the performance obtained by sprint swimmers over very-short distances. As aforementioned, it is plausible that the mechanical principles that determine the shape of the force-velocity curve are also able to increase the association between these variables. In jump squats, the power output may be maximized across a moderate range of the load spectrum [11,22,33] (from 30 to 70% of 1RM), with the movements being executed as

rapidly as possible. These mechanical characteristics (i.e., moderate force applied at high submaximal velocities) are very similar to those usually found by aquatic athletes when performing sprint crawl swimming [35,59]. Furthermore, our actual tests were conducted in a 25-m swimming pool, with the swimmers starting from a block and presumably executing a powerful "push-off" (against the pool wall) during the freestyle flip-turn [34]. Certainly, these explosive and closed kinetic chain movements are largely related to the ability to generate higher levels of power output using the lower limbs [7,8,14,30,32]. Taken together, these neuromechanical aspects possibly support the high correlation between vertical loaded jumps and 50-m swim times presented herein.

In summary, our data suggest that 10-sec tethered swimming is an excellent tool for measuring the specific propulsive forces that determine the swimmers' performance in 50- and 100-m freestyle swimming. This result relates to the specific duration of the tethered and freestyle swimming assessments, limiting the generalization of our findings to performances obtained in longer distances (i.e., >100-m). Although the time-dependent variables (IMP and RFD) were only related to the very-short distances (i.e., 50-m), the F_{AVG} and F_{PEAK} strongly explained 50- and 100-m swim times. The standardized leg power tests executed in a dry-land setting (i.e., JS, SJ and CMJ) presented strong correlations with tethered swimming ($r \approx 0.70$), indicating that the capacity to generate power using the lower limbs plays a crucial role in influencing the magnitude of the tether forces. Finally, the mean propulsive power collected during jump squats was largely associated with 50-m sprint swimming performance. It appears that the ability to produce higher levels of muscle power using the lower limbs – even in dry-land assessments/exercises – has fundamental importance in enhancing the sprint swimmers' competitiveness.

One shortcoming of this study was the limited number of upper body exercises tested, despite its relatively high contribution in swimming performance. It remains to be established whether strength and power measured in other exercises such as prone bench pull and shoulder press are related to tethered or actual swimming performance. Secondly, a further study must be developed to investigate the effects of training using loaded or unloaded jumps on tethered and freestyle swimming performance.

Conclusion
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Based on the results presented herein, head, strength and conditioning coaches are strongly encouraged to utilize loaded and unloaded vertical jumps to improve swimmers' performance, both in tethered and in actual sprint swimming. Monitoring specific adaptations after periods of training that comprise jump squats and plyometrics in their routines will further permit quantification as to what extent improvements in dry-land neuromechanical measures would transfer to tether dynamic parameters and free-style swimming. It is also important to determine whether our results would remain consistent in 50-m swimming pools given that, in 25-m length pools, powerful "push-offs" are more prevalent than in longer ones. More studies are needed to verify the relationships between other upper limb strength-power exercises (e.g., shoulder press and rowing exercises) and swimmers' performance. Finally, tethered swimming was shown to be useful to quantify dynamic parameters of

aquatic athletes, as it allows researchers to mediate the transference between dry-land exercises/assessments and actual sprint swimming performance.

Acknowledgements
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References
1 *Aagaard P, Simonsen EB, Andersen JL, Magnusson P, Dyhre-Poulsen P.* Increased rate of force development and neural drive of human skeletal muscle following resistance training. J Appl Physiol 2002; 93: 1318–1326
2 *Aagaard P, Simonsen EB, Trolle M, Bangsbo J, Klausen K.* Specificity of training velocity and training load on gains in isokinetic knee joint strength. Acta Physiol Scand 1996; 156: 123–129
3 *Alptekin A.* Body composition and kinematic analysis of the grab start in youth swimmers. J Hum Kinet 2014; 42: 15–26
4 *Andersen LL, Aagaard P.* Influence of maximal muscle strength and intrinsic muscle contractile properties on contractile rate of force development. Eur J Appl Physiol 2006; 96: 46–52
5 *Araujo L, Pereira S, Gatti R, Freitas E, Jacomel G, Roesler H, Villas-Boas J.* Analysis of the lateral push-off in the freestyle flip turn. J Sports Sci 2010; 28: 1175–1181
6 *Aspenes S, Kjendlie PL, Hoff J, Helgerud J.* Combined strength and endurance training in competitive swimmers. J Sports Sci Med 2009; 8: 357–365
7 *Baker D, Nance S.* The relation between running speed and measures of strength and power in professional rugby league players. J Strength Cond Res 1999; 13: 230–235
8 *Baker D, Nance S.* The relation between strength and power in professional rugby league players. J Strength Cond Res 1999; 13: 224–229
9 *Barbosa AC, Castro Fde S, Dopsaj M, Cunha SA, Andries O Jr.* Acute responses of biomechanical parameters to different sizes of hand paddles in front-crawl stroke. J Sports Sci 2013; 31: 1015–1023
10 *Bazyler CD, Beckham GK, Sato K.* The use of the isometric squat as a measure of strength and explosiveness. J Strength Cond Res 2015; 29: 1386–1392
11 *Cormie P, McCaulley GO, Triplett NT, McBride JM.* Optimal loading for maximal power output during lower-body resistance exercises. Med Sci Sports Exerc 2007; 39: 340–349
12 *Costill DL, Kovaleski J, Porter D, Kirwan J, Fielding R, King D.* Energy expenditure during front crawl swimming: predicting success in middle-distance events. Int J Sports Med 1985; 6: 266–270
13 *Craig AB Jr, Pendergast DR.* Relationships of stroke rate, distance per stroke, and velocity in competitive swimming. Med Sci Sports 1979; 11: 278–283
14 *Cronin JB, Hansen KT.* Strength and power predictors of sports speed. J Strength Cond Res 2005; 19: 349–357
15 *Cronin JB, McNair PJ, Marshall RN.* Is velocity-specific strength training important in improving functional performance? J Sports Med Phys Fitness 2002; 42: 267–273
16 *Crowe SE, Babington JP, Tanner DA, Stager JM.* The relationship of strength to dryland power, swimming power, and swimming performance. Med Sci Sports Exerc 1999; 31: S255
17 *Dopsaj M, Matkovic I, Thanopoulos V, Okičić T.* Reliability and validity of basic kinematics and mechanical characteristics of pulling force in swimmers measured by the method of tethered swimming with maximum intensity of 60 seconds. Phys Educ Sport 2003; 1: 11–22
18 *Dopsaj M, Matkovic I, Zdravkovic I.* The relationship between 50 m-freestyle results and characteristics of tethered forces in male sprint swimmers: A new approach to tethered swimming test. Phys Educ Sport 2000; 1: 15–22
19 *Girold S, Maurin D, Dugue B, Chatard JC, Millet G.* Effects of dry-land vs. resisted- and assisted-sprint exercises on swimming sprint performances. J Strength Cond Res 2007; 21: 599–605
20 *Gourgoulis V, Aggeloussis N, Vezos N, Antoniou P, Mavromatis G.* Hand orientation in hand paddle swimming. Int J Sports Med 2008; 29: 429–434
21 *Gourgoulis V, Boli A, Aggeloussis N, Toubekis A, Antoniou P, Kasimatis P, Vezos N, Michalopoulou M, Kambas A, Mavromatis G.* The effect of leg kick on sprint front crawl swimming. J Sports Sci 2014; 32: 278–289
22 *Harris NK, Cronin JB, Hopkins WG, Hansen KT.* Squat jump training at maximal power loads vs. heavy loads: effect on sprint ability. J Strength Cond Res 2008; 22: 1742–1749
23 *Harriss DJ, Atkinson G.* Ethical standards in sport and exercise science research: 2014 update. Int J Sports Med 2013; 34: 1025–1028
24 *Hopkins WG.* A Scale of Magnitudes for Effect Statistics. 2002; Available from: http://www.sportsci.org/resource/stats/effectmag.html
25 *Ingebrigtsen J, Holtermann A, Roeleveld K.* Effects of load and contraction velocity during three-week biceps curls training on isometric and isokinetic performance. J Strength Cond Res 2009; 23: 1670–1676
26 *Johnson RE, Sharp RL, Hedrick CE.* Relationship of swimming power and dryland power to sprint freestyle performance: a multiple regression approach. J Swim Res 1993; 9: 10–14
27 *Kanehisa H, Miyashita M.* Specificity of velocity in strength training. Eur J Appl Physiol 1983; 52: 104–106
28 *Kaneko M, Fuchimoto T, Toji H, Suei K.* Training effect of different loads on the force/velocity relationship and mechanical power output in human muscle. Scand J Sports Sci 1983; 5: 50–55
29 *Keskinen OP, Keskinen KL, Mero AA.* Effect of pool length on blood lactate, heart rate, and velocity in swimming. Int J Sports Med 2007; 28: 407–413
30 *Loturco I, D'Angelo RA, Fernandes V, Gil S, Kobal R, Abad CCC, Kitamura K, Nakamura FY.* Relationship between sprint ability and loaded/unloaded jump tests in elite sprinters. J Strength Cond Res 2015; 29: 758–764
31 *Loturco I, Kobal R, Gil S, Pivetti B, Kitamura K, Pereira LA, Abad CC, Nakamura FY.* Differences in loaded and unloaded vertical jumping ability and sprinting performance between Brazilian elite under-20 and senior soccer players. Am J Sports Sci 2014; 2: 8–13
32 *Loturco I, Pereira LA, Cal Abad CC, D'Angelo RA, Fernandes V, Kitamura K, Kobal R, Nakamura FY.* Vertical and vorizontal jump tests are strongly associated with competitive performance in 100-m dash events. J Strength Cond Res 2015; 29: 1966–1971
33 *Loturco I, Ugrinowitsch C, Roschel H, Tricoli V, Gonzalez-Badillo JJ.* Training at the optimum power zone produces similar performance improvements to traditional strength training. J Sports Sci Med 2013; 12: 109–115
34 *Lyttle AD, Blanksby BA, Elliott BC, Lloyd DG.* Investigating kinetics in the freestyle flip turn push-off. J Appl Biomech 1999; 15: 242–252
35 *McCabe CB, Psycharakis S, Sanders R.* Kinematic differences between front crawl sprint and distance swimmers at sprint pace. J Sports Sci 2011; 29: 115–123
36 *McGuigan MR, Winchester JB.* The relationship between isometric and dynamic strength in college football players. J Sports Sci Med 2008; 7: 101–105
37 *Monod H, Scherrer J.* The work capacity of a synergic muscular group. Ergonomics 1965; 8: 329–338
38 *Morouco P, Keskinen KL, Vilas-Boas JP, Fernandes RJ.* Relationship between tethered forces and the four swimming techniques performance. J Appl Biomech 2011; 27: 161–169
39 *Morouco P, Neiva H, Gonzalez-Badillo JJ, Garrido N, Marinho DA, Marques MC.* Associations between dry land strength and power measurements with swimming performance in elite athletes: a pilot study. J Hum Kinet 2011; 29A: 105–112
40 *Morouco PG, Marinho DA, Amaro NM, Pérez-Turpin JA, Marques MC.* Effects of dry-land strength training on swimming performance: a brief review. J Hum Sport Exerc 2012; 7: 553–559
41 *Morouco PG, Marinho DA, Keskinen KL, Badillo JJ, Marques MC.* Tethered swimming can be used to evaluate force contribution for short-distance swimming performance. J Strength Cond Res 2014; 28: 3093–3099

42 *Neiva H, Morouco P, Silva AJ, Marques MC, Marinho DA.* The effect of warm-up on tethered front crawl swimming forces. J Hum Kinet 2011; 29A: 113–119

43 *Newton RU, Kraemer WJ, Hakkinen K.* Effects of ballistic training on preseason preparation of elite volleyball players. Med Sci Sports Exerc 1999; 31: 323–330

44 *Newton RU, Rogers RA, Volek JS, Hakkinen K, Kraemer WJ.* Four weeks of optimal load ballistic resistance training at the end of season attenuates declining jump performance of women volleyball players. J Strength Cond Res 2006; 20: 955–961

45 *Papoti M, da Silva AS, Araujo GG, Santiago V, Martins LE, Cunha SA, Gobatto CA.* Aerobic and anaerobic performances in tethered swimming. Int J Sports Med 2013; 34: 712–719

46 *Sanchez-Medina L, Perez CE, Gonzalez-Badillo JJ.* Importance of the propulsive phase in strength assessment. Int J Sports Med 2010; 31: 123–129

47 *Sanders RH.* Kinematics, coordination, variability, and biological noise in the prone flutter kick at different levels of a "learn-to-swim" program. J Sports Sci 2007; 25: 213–227

48 *Santos KB, Bento PC, Pereira G, Rodacki AL.* The relationship between propulsive force in tethered-swimming and 200m-front crawl performance. J Strength Cond Res 2014 in press

49 *Sharp RL, Troup JP, Costill DL.* Relationship between power and sprint freestyle swimming. Med Sci Sports Exerc 1982; 14: 53–56

50 *Strzała M, Tyka A.* Physical endurance, somatic indices and swimming technique parameters as determinants of front crawl swimming speed at short distances in young swimmers. Med Sport 2009; 13: 99–107

51 *Strzała M, Tyka A, Krezalek P.* Swimming technique and biometric and functional indices of young swimmers in relation to front crawl swimming velocity. Hum Mov 2007; 8: 112–119

52 *Tanaka H, Swensen T.* Impact of resistance training on endurance performance. A new form of cross-training? Sports Med 1998; 25: 191–200

53 *Terzis G, Georgiadis G, Vassiliadou E, Manta P.* Relationship between shot put performance and triceps brachii fiber type composition and power production. Eur J Appl Physiol 2003; 90: 10–15

54 *Toussaint HM, Hollander AP, Van den Berg C, Vorontsov AR.* Biomechanics in Swimming. In: Garrett WE, Kirkendall DT (eds.). Exercise and sport Science. Philadelphia: Lippincott, Williams & Wilkins; 2000

55 *Toussaint HM, Truijens M.* Power requirements for swimming a world-record 50-m front crawl. Int J Sports Physiol Perform 2006; 1: 61–64

56 *Ugarkovic D, Matavulj D, Kukolj M, Jaric S.* Standard anthropometric, body composition, and strength variables as predictors of jumping performance in elite junior athletes. J Strength Cond Res 2002; 16: 227–230

57 *Van Cutsem M, Duchateau J.* Preceding muscle activity influences motor unit discharge and rate of torque development during ballistic contractions in humans. J Physiol 2005; 562: 635–644

58 *Walsh MS, Ford KR, Bangen KJ, Myer GD, Hewett TE.* The validation of a portable force plate for measuring force-time data during jumping and landing tasks. J Strength Cond Res 2006; 20: 730–734

59 *Wilke K.* Analysis of sprint swimming: The 50 m freestyle. In: McLaren D, Reilly T, Lees A (eds.). Biomechanics and medicine in swimming VI. Abingdon: Routledge; 1992

60 *Wilson GJ, Murphy AJ.* The use of isometric tests of muscular function in athletic assessment. Sports Med 1996; 22: 19–37

61 *Winter DA* (ed.). Biomechanics and Motor Control of Human Movement. New York: John Wiley & Sons; 1990

62 *Yeater RA, Martin RB, White MK, Gilson KH.* Tethered swimming forces in the crawl, breast and back strokes and their relationship to competitive performance. J Biomech 1981; 14: 527–537