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Relationship Between Tethered Forces and the Four Swimming Techniques Performance

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The purpose of the current study was to identify the relationships between competitive performance and tether forces according to distance swam, in the four strokes, and to analyze if relative values of force production are better determinants of swimming performance than absolute values. The subjects (n = 32) performed a 30 s tethered swimming all-out effort. The competitive swimming velocities were obtained in the distances 50, 100 and 200 m using official chronometric values of competitions within 25 days after testing protocol. Mean force and velocity (50 m event) show significant correlations for front crawl (r = .92, p < .01), backstroke (r = .81, p < .05), breaststroke (r = .94, p < .01) and butterfly (r = .92, p < .01). The data suggests that absolute values of force production are more associated to competitive performance than relative values (normalized to body mass). Tethered swimming test seems to be a reliable protocol to evaluate the swimmer stroking force production and a helpful estimator of competitive performance in short distance competitive events.

Keywords: biomechanics, strength, front crawl, backstroke, breaststroke, butterfly

It seems evident that propulsion, and estimation of propulsive force, is an important determinant of swimming performance (Lauder et al., 2001; Matsuuchi et al., 2009; Sanders & Psycharakis, 2009). However, the locomotion in the aquatic environment is highly complex, being difficult to assess the magnitude of these forces. On the other hand, swimming in the same spot, i.e., tethered swimming, enhances the possibility of measuring the maximum force that, theoretically, corresponds to the propelling force that a swimmer must produce to overcome the water resistance at maximum free-swim velocity (Yeater et al., 1981; Dopsaj et al., 2003). Thus, tethered swimming has been pointed as one of the most specific swimming ergometer, simulating the environment characteristics, stroke mechanics, physiological aspects and body anthropometry and morphological influence (Filho & Denadai, 2008).

In this sense, as the swimmers' velocity increases, a higher drag, in a quadratic relation, is produced, which oblige to put emphasis on the propulsive force (Hollander et al., 1986). In previous studies, researchers have tried to estimate the above-referred forces (e.g., Shimonagata et al., 1999). More specifically, Wilke & Madsen (1990) stated that as the swimming distance diminishes, the role of maximum force increases, and as the distance increases, the endurance force takes a major role. However, this phenomenon has not been extensively studied.

Swimming velocity has been successfully correlated with upper body anaerobic power in dryland testing for the front crawl technique (Sharp et al., 1982; Hawley et al., 1992; Hopper et al., 1983). Conversely, these methodologies using only the arms neglect the role of the legs and their importance for body coordination, and even propulsion (Yeater et al., 1981; Costill et al., 1983; Yanai, 2001).The above referred studies focused only on front crawl technique and, despite the apparent similarities between the arm actions in biokinetic strength test and sprint swimming, only measurements conducted in the water are truly specific to the assessment of the propulsive forces in this swimming technique (Costill et al., 1986).

In contrast, trying to achieve a more specific approach for swimming performance, tethered swimming has been pointed as a useful tool (Magel, 1970; Yeater et al., 1981; Kjendlie & Thorsvald, 2006), being shown that it is similar to free swimming (Christensen & Smith, 1987). Magel (1970) suggested this methodology to assess the propulsive force exerted by arms and legs in the four competitive swimming techniques, noticing that the breaststroke and butterfly techniques produced

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the highest peak forces. After this pioneer characterization, studies evaluating the relationship between force production in tethered swimming and swimming performance were scarcely developed. Yeater et al. (1981) studied the relationship between swimming velocity and mean maximum force in front crawl, backstroke and breaststroke, obtaining a high correlation for the front crawl technique. Afterward, knowing that a significant relationship between the above referred parameters were obtained only for front crawl, other studies were conducted in this technique, involving mainly short distance tests (Costill et al., 1986; Christensen & Smith, 1987; Keskinen et al., 1989; Fomitchenko, 1999). Only in the final of 1990s D'Acquisto & Costill (1998) obtained a significant relationship between swimming power and sprint performance in other technique than front crawl: breaststroke.

In the specialized literature, the only tethered swimming related study that was conducted in the four swimming competitive techniques used an apparatus that measured the power delivered by the swimmer to an external weight, not assessing the real power developed by the swimmer (Hopper et al., 1983). It was observed inverse relationships between power per stroke and 50 m time for each swimming technique. Nonetheless, this study was performed with a heterogeneous sample, with subjects of different swimming and strength abilities, analyzing indifferently men, women, elite and recreational swimmers.

Thus, the relationship between force production and swimming performance has been analyzed in some studies but these approaches focused mainly in front crawl swimming and used short swimming distances (e.g., 10 m and 25 m). The aims of the current study were to characterize the force profiles of elite swimmers, through tethered swimming, in the four competitive techniques, identify the relationship between tether forces and swimming velocities, and to see if relative values of force production are better estimators of swimming performance than absolute values.

Methods

Subjects

Thirty-two international level swimmers (20 male and 12 female) volunteered to participate in this study, and signed an informed consent in which the experimental protocol was described. The Ethics Committee of the hosting University approved the experimental protocol. The swimmers suffered neither from illness nor from restrictions that hindered their performances during events. Mean ± *SD* values for the main physical and performance characteristics of the subjects are described in Table 1, according to gender.

Body mass, fat, and lean body mass were assessed through a bioelectric impedance analysis method (Tanita BC 420S MA, Japan). Body mass index was calculated with the traditionally used formula:

$$\text{BMI} = \text{Body Mass} \times \text{Height}^{-2} \tag{1}$$

The surface area was estimated using the equation of Du Bois & Du Bois (1989):

$$\text{SA} = \text{Height}^{0.655} \times \text{Body Mass}^{0.441} \times 94.9 \tag{2}$$

Testing Protocol

Tests were conducted in a 50 m indoor swimming pool (27 °C of water temperature) during the competitive period of the winter macrocycle to ensure that the subjects were in a high training stage. After a 1200 m low intensity warm-up, each subject performed two 30 s all-out tethered swimming tests: one in front crawl and the other in his/her other best stroke. A 10 min rest between trials was observed. The subjects were wearing a belt attached to a steel cable (sufficiently stiff that its elasticity could be neglected) with 5 m length, and with a 5.7° angle in relation to the water surface. A load-cell system connected to the cable was used as a measuring device, recording at 100 Hz with a measure capacity of 5000 N.

Table 1 Main physical and performance characteristics of the subjects (according to gender)

	Male (*n* = 20)	Female (*n* = 12)
Age (years)	19.0 ± 2.88*	15.3 ± 1.68
Height (cm)	181.4 ± 7.09*	166.1 ± 5.20
Body mass (kg)	74.8 ± 6.42*	54.5 ± 6.07
Body mass index ($kg{\cdot}m^{-2}$)	22.8 ± 1.53*	19.7 ± 1.25
Fat (kg)	7.9 ± 2.92*	11.6 ± 2.71
Lean body mass (kg)	66.9 ± 6.87*	42.9 ± 3.66
Surface area (m^2)	1.92 ± 0.11*	1.57 ± 0.11
100 freestyle (FINA points)	721.0 ± 58.5	687.6 ± 37.6

*Significant difference between the two gender groups ($p < .05$).

The load-cell was connected to a Globus Ergometer data acquisition system (Globus, Italy) that exported the data in ASCII format to a PC. Preceding the starting signal, swimmers adopted a horizontal position with the cable fully extended, starting the data collection only after the first stroke cycle was completed. This procedure was used to avoid the inertial effect of the cable extension usually produced immediately before or during the first arm action. The end of the test was set through an acoustic signal. The swimmers were told to follow the breathing pattern they would normally apply during a race.

Data Analysis

Individual force to time, F(t), curves were assessed and registered to obtain the following parameters: maximum force (Fmax, the highest value of force produced in first 10 s) absolute and relative values, mean force (Fmean, average force values during the 30 s test) absolute and relative values, and fatigue index (Fatindex), being the relative decrease of force from its highest peak registered in the first 10 s to its minimum peak obtained in the last 5 s of the test, Fatindex = [(maximum peak – minimum peak) / maximum peak] × 100. The swimming velocities were obtained by the official electronic chronometric times of long course swimming competitions within the 25 days following the tethered swimming experiments.

Statistical Analysis

The assumed normality (Kolmogorov–Smirnov normality test) was verified for all the variables before the analysis. To obtain the descriptive statistics (mean, *SD*) standard statistical methods were used. A one-way ANOVA (post hoc Bonferroni) for independent samples to establish differences between the values of the four competitive strokes was applied. To establish relationships between variables, Pearson's correlation coefficient (r) was used for each competitive stroke and swimming velocity. In addition, linear regression analysis was used assessing regression coefficient (r^2) together with the Passing–Bablok parameters (intercept, slope). The level of statistical significance was set at $p < .05$.

Results

Tethered Force Analysis

Representative tethered force profiles for the four competitive strokes are shown in Figure 1. To achieve higher propulsion, the swimmers should apply the propulsive forces in the correct sequence, according to the different phases of the stroke. An upward trace on the force recording profile indicates that effective propulsion obtained by force exerted in water increases. Complementarily, a downward trace indicates that the force exerted in water decreased, possibly being coincident with the minor propulsive phases in front crawl and backstroke, and with the arms and the legs recovery phases in butterfly and breaststroke, respectively. Moreover, a shorter gap between two upward traces indicates a higher frequency of propulsive movements. In the illustration it can be observed that, in breaststroke and butterfly techniques, force values reaches zero between each stroke cycle.

In Table 2 it is possible to observe the mean ± *SD* values for the tethered force variables and swimming velocity, grouped by swimming technique. The higher values of absolute maximum force production were obtained in breaststroke, butterfly, front crawl and backstroke, respectively (statistical differences between techniques are identified). Similar behavior was observed regarding the relative values of force production. Conversely, no differences were reported for the mean force parameter (absolute values), except between breaststroke and butterfly when expressed in relative values. The fatigue index did not differ between swimming techniques, presenting breaststroke a tendency for lower values. Concerning the performance parameters, front crawl presented lower duration for the three selected events, followed by butterfly, backstroke and breaststroke.

Relationship Between Variables

The relationship between swimming velocities and tethered force parameters, are displayed in Table 3, for each swimming technique. A significant correlation was observed between Fmax absolute values and swimming velocities, in the four swimming techniques (ranging from 0.61 to 0.94), except for v200 breaststroke. The relative Fmax production only presented significant relationships with v50 and v100 performed in front crawl. The average force production during the 30 s test significantly correlated with swimming velocities, for the four strokes (ranging from 0.78 to 0.94). When normalized to body mass this parameter presented significant correlations with the three swimming events in front crawl and butterfly. Regarding Fatindex, it is possible to observe direct relationships with the front crawl performance variable, probably due to larger number of the freestyle data points. For a better observation of the behavior of the most significant correlation values between the swimming velocity and power (Fmax and Fmean) with distance swum, Figure 2 is also displayed.

In Figure 3 it is represented the relationship between Fmean absolute values and swimming velocities in the 50 m events, according to swimming techniques (determination coefficient ranging from 0.71 to 0.88). Linear regression equation is presented for each technique.

Discussion

The aims of this study were to characterize the force profiles of international level swimmers, obtained through tethered swimming in the four competitive techniques, as

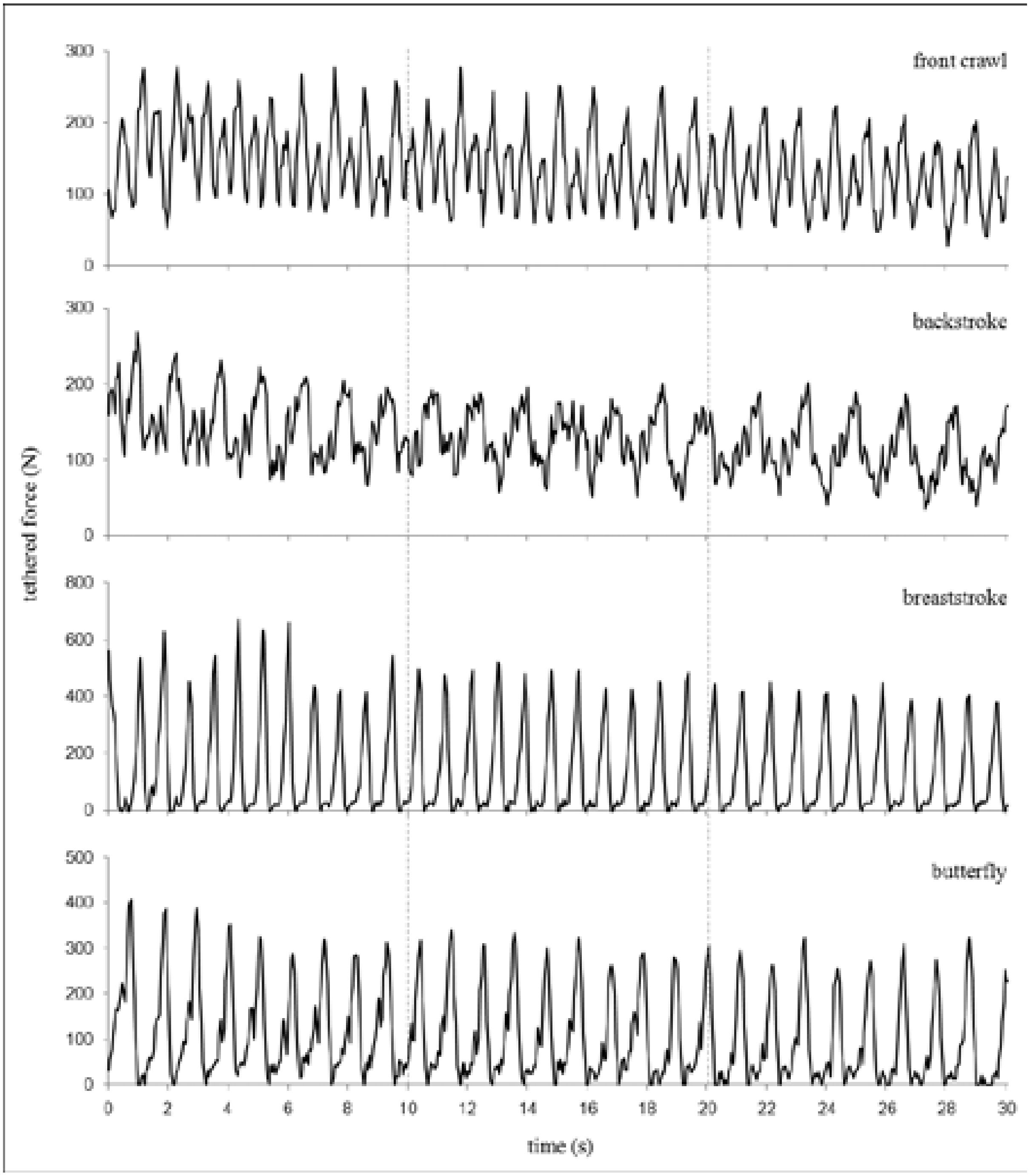

Figure 1 — Individual examples of typical force profiles in a 30 s tethered swimming test for front crawl, backstroke, breaststroke and butterfly techniques.

well as to assess its relationship with swimming performance. The experimentations were conducted in normal swimming pool conditions, using appropriate techniques (cf. Dopsaj et al., 2003; Kjendlie & Thorsvald, 2006), which allowed real time access to data. The used methodology allowed gathering individual, easy to obtain and up to date information related with the propulsive force that swimmers can exert in each competitive swimming technique.

Tethered Force Analysis

Load cell system recording provides a permanent measurement of propelling force exerted during tethered

Table 2 Analysis of tethered forces variables and swimming velocity, according to technique

	Fmax (N)	Fmax ($N \cdot kg^{-1}$)	Fmean (N)	Fmean ($N \cdot kg^{-1}$)	Fatindex (%)	v50 ($m \cdot s^{-1}$)	v100 ($m \cdot s^{-1}$)	v200 ($m \cdot s^{-1}$)
Front crawl (*n* = 32)	232.6 ± 63.2[a,b]	3.43 ± 0.68[a,b]	92.8 ± 33.7	1.34 ± 0.36	37.59 ± 8.24	1.92 ± 0.16[a,b]	1.77 ± 0.14[a]	1.64 ± 0.13[a,b]
Backstroke (*n* = 8)	211.6 ± 47.5[c,d]	3.13 ± 0.47[c,d]	99.9 ± 29.1	1.47 ± 0.27	36.39 ± 8.05	1.71 ± 0.12[a]	1.62 ± 0.09[b]	1.52 ± 0.09[c]
Breaststroke (*n* = 8)	513.0 ± 153.9[a,c,e]	7.35 ± 1.26[a,c,e]	115.6 ± 30.5	1.68 ± 0.26[a]	30.88 ± 7.21	1.58 ± 0.09[b,c]	1.45 ± 0.09[a,b,c]	1.33 ± 0.11[a,c,d]
Butterfly (*n* = 16)	394.4 ± 134.4[b,d,e]	5.63 ± 1.45[b,d,e]	88.9 ± 34.9	1.25 ± 0.33[a]	38.66 ± 9.75	1.81 ± 0.18[c]	1.67 ± 0.16[c]	1.50 ± 0.15[b,d]

Note. Fmax, absolute maximum force; Fmean, mean force; Fatindex, fatigue index; v50, velocity for the 50 m event; v100, velocity for the 100 m event; v200, velocity for the 200 m event.
[a,b,c,d,e] Represent significant differences between techniques ($p < .05$).

Table 3 Correlation values (Pearson *r*) between swimming velocities and tethered force parameters in four swimming techniques

	Front crawl (*n* = 32)			Backstroke (*n* = 8)			Breaststroke (*n* = 8)			Butterfly (*n* = 16)		
	v50	v100	v200	v50	v100	v200	v50	v100	v200	v50	v100	v200
Fmax (N)	-0.77**	-0.77**	-0.71**	-0.86**	-0.89**	-0.94**	-0.90**	-0.77*	-0.66	-0.69**	-0.73**	-0.61*
Fmax ($N \cdot kg^{-1}$)	-0.47**	-0.45*	-0.34	-0.36	-0.42	-0.55	-0.37	-0.13	-0.15	-0.31	-0.31	-0.15
Fmean (N)	-0.92**	-0.91**	-0.82**	-0.81*	-0.78*	-0.78*	-0.94**	-0.86**	-0.80*	-0.92**	-0.93**	-0.90**
Fmean ($N \cdot kg^{-1}$)	-0.85**	-0.82**	-0.69**	-0.59	-0.56	-0.61	-0.36	-0.23	-0.21	-0.91**	-0.89**	-0.83**
Fatindex (%)	0.44*	0.39*	0.41*	0.20	0.17	0.16	-0.35	-0.23	-0.14	0.24	0.26	0.32

Note. Fmax, maximum force; Fmean, mean force; Fatind, fatigue index; v50, velocity for the 50 m event; v100, velocity for the 100 m event; v200, velocity for the 200 m event.
*Significant correlation for $p < .05$ and ** for $p < .01$.

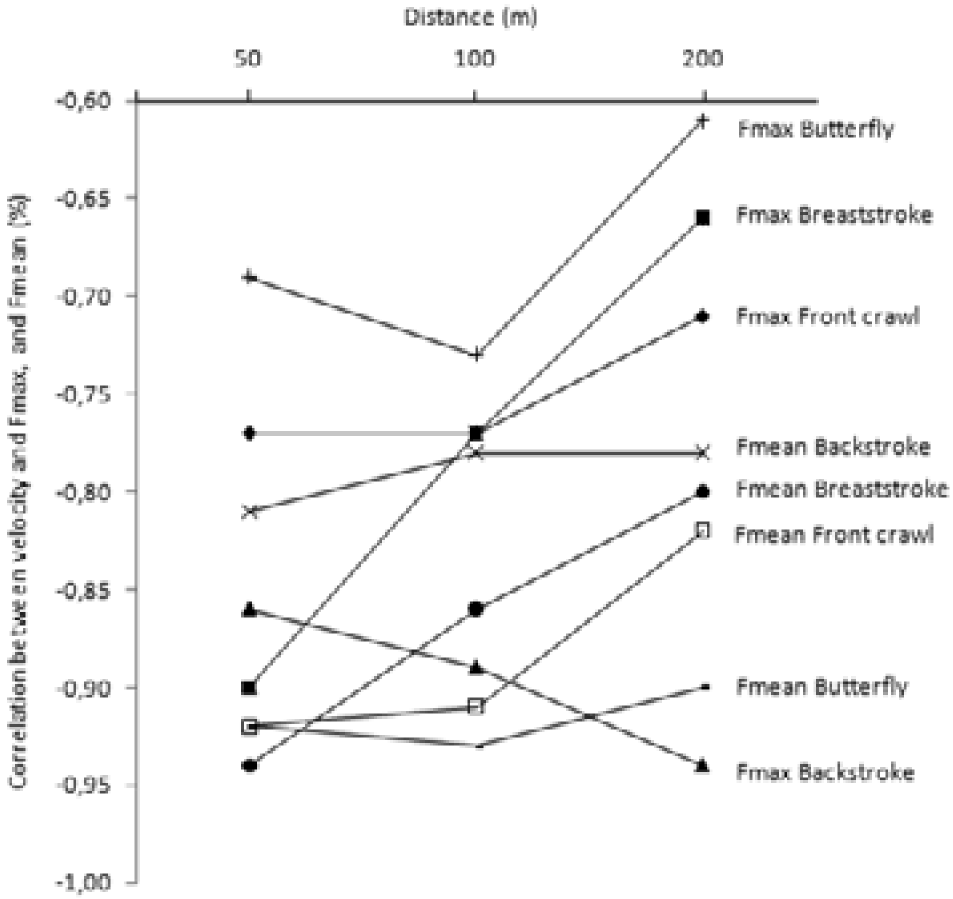

Figure 2 — Behavior of the relationships between swimming velocity and Fmax, and Fmean (by swimming technique) with distance swum.

swimming. Assessing individual F(t) curves improves the possibility of analysis and comparison of stroke profiles, and allow to more accurately know the sequence of propulsive forces during swimming (Keskinen, 1997). From our data, it was observed a decline in force production during the 30 s test for all swimming techniques, which has been suggested to be due to fatigue (Stager & Coyle, 2005). In addition, a periodical variation of propulsive force during each stroke is shown, resulting in either acceleration or deceleration of the body (Alves et al., 1995). Moreover, different profiles are obtained according to the different swimming techniques analyzed, presenting the simultaneous techniques (breaststroke and butterfly) both higher and lower values of force production, inducing maximum forces higher than the alternated techniques (front crawl and backstroke). This fact seems to be due to the simultaneous actions of both arms and legs, which ensue in higher intracycle velocity variation (Barbosa et al., 2006; Craig et al., 2006). However, it should also be considered that when the force goes to zero, the cable becomes slack, and the retensioning of the cable could result in a stress wave that will cause a spike in the force measurement. Future studies should try to avoid this phenomenon.

The Fmax absolute values obtained for front crawl are higher than the majority of values previously presented in the specialized literature. These differences seem to be justified by the different swimming competitive levels and the different tethered swimming methodologies used (Adams II, et al., 1983; Keskinen, 1997; Hooper et al., 1998). Complementarily, the number of studies developed in breaststroke, backstroke and butterfly are scarce, which weakens its comparison with our data. The fact that breaststroke swimmers recorded the highest tethered swimming force values can be explained by the powerful leg kick characteristic of this technique in opposition of the legs action of butterfly, front crawl and backstroke that are dominantly used for body balance (Maglischo, 2003; Craig et al., 2006). However, breaststroke is the slowest of the four conventional swimming techniques, which seems to be justified by an over-water recovery of the arms and by the higher discontinuity of the synchronization of arms and legs, as well as by the overlapping propulsive movements of the other techniques, which allow a more effective use of propulsive force, probably accounting for the higher velocities attained (Maglischo, 2003; Barbosa et al., 2006; Craig et al., 2006).

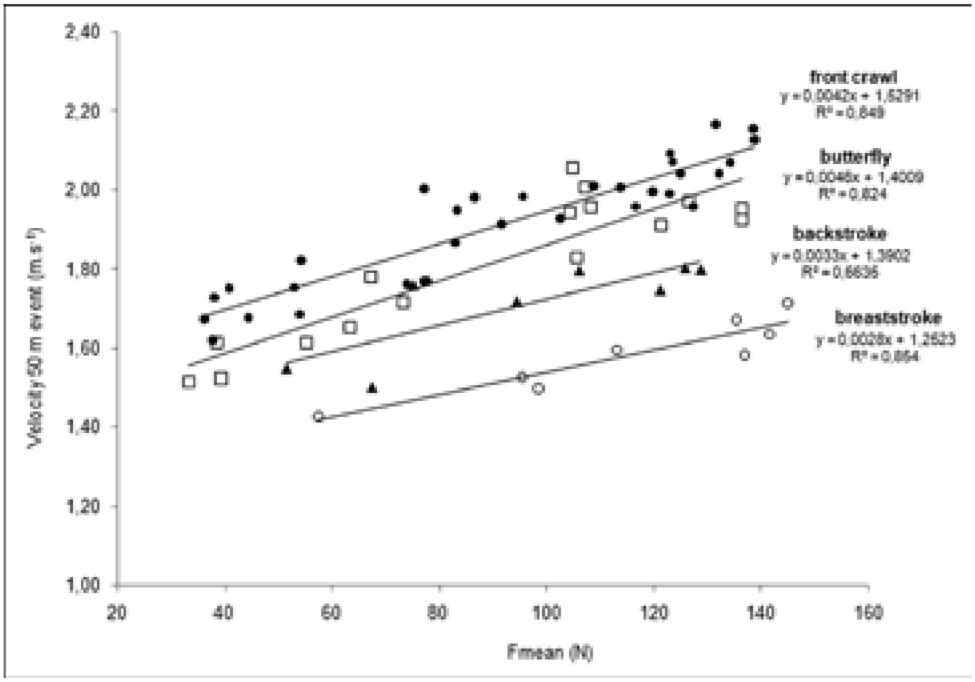

Figure 3 — Relationship between Fmean absolute values in 30 s tethered test and velocity in the 50 m competitive event according to swimming technique.

Relationship Between Variables

Some studies have been developed suggesting that the velocity obtained in short duration efforts is well related to the stroking force that a swimmer can generate (e.g., Costill et al., 1986). The assessment of this data may be an individual approach to the anaerobic evaluation of the swimmer and, therefore, a helpful procedure to coaches (Soares et al., 2010). However, most of these studies were conducted in the front crawl technique and in non-competitive swimming distances (less than 50 m). Most of conducted studies used dry-land testing with biokinetic swimbench (e.g., Sharp et al., 1982; Hawley et al., 1992). However, Costill et al. (1986) stated that only measurements of force production exerted in water are reliable to evaluate the capacity of the swimmer to use is muscular strength in effectively propulsive swimming force. Complementarily, the swimming stroke is characterized by a complex series of sculls and diagonal movement which cannot be replicated in dry land testing techniques (Hopper et al., 1983)

The current study presented several significant relationships between parameters obtained through tethered swimming and competitive performance in short and middle distances. Firstly, it was observed strong relationship between Fmean absolute and v50 for the four swimming techniques. The correlations between absolute Fmean and front crawl swimming velocity are higher than those previously published, and obtained with less proficient swimmers (Yeater et al., 1981; Costill et al., 1983). Secondly, the relationship between Fmax absolute values and v50 in all swimming techniques indicates that the more the swimmers were able to increase absolute force, the higher swimming velocities were attained in competitive events. These suggestions are in agreement with the literature, namely with Costill et al. (1986) who observed that although velocity correlated significantly with swim power measured through tethered swimming, no relationship was obtained when biokinetic swimbench was used.

Previous studies in breaststroke swimming force production have demonstrated higher values of correlation between force and a sprint event, than with a middle distance event (D'Acquisto & Costill, 1998). In the current study, this fact is observed in all the swimming techniques, being obtained higher correlations between force parameters and v50, than with v100 and even lower values with v200. The force parameter that presented higher correlation value with the competitive events performance was absolute Fmean, being shown that the strength of the relationships diminish with the competitive distance increase. This data seems to indicate that the force exerted in water is a major important factor for success in swimming performance, being its importance increased as the competitive distance diminishes.

The average force that a swimmer can exert during a 30 s all-out effort test appears to be a possible methodology to evaluate the anaerobic capacity of a swimmer (Soares et al., 2010). Accordingly, the competitive technique with higher correlation values with v50 was breaststroke, followed by front crawl, butterfly and backstroke, which seems to be in accordance with the only study that was conducted in the four competitive techniques (Hopper et al., 1983). These authors obtained higher correlations between power and performance for breaststroke (r = -0.90), followed by butterfly (r = -0.89), backstroke (r = -0.84) and freestyle (r = -0.80).

The relationship between forces exerted in water with swimming performance other than front crawl technique is relatively unknown. The present study is the first to address the contribution of strength to the four swimming techniques, according to different competitive distance events. In addition, the used methodology may have some potential in evaluation for sprint and endurance swimming (Stager & Coyle, 2005). Corroborating Yeater et al. (1981), normalizing the force data by body mass did not improve the correlations, for mean and maximum values. Although force production capacity might be expected to scale with muscle mass and thus with full body mass, this particular relationship in swimming may be affected by specific swimming ability, evidencing the subjects' capacity to apply force in water. This effect was emphasized long ago by Miyashita (1975), by relating maximal arm swimming velocity with arm strength, both in male and female swimmers and non-proficient swimmers. It is concluded that propulsive force, as measured in this study, offers an objective assessment of an essential component for success in short distance swimming. The significant correlations of tethered swimming parameters obtained in an all-out 30 s test and swimming competitive performance suggest that, to improve swimming performance, the swimmer should improve stroking force production. An individual analysis of the graphic recordings illustrated that a large number of subjects had a marked difference in peak force between arm pulls. This may be a helpful tool for coach evaluation in effectiveness of swimmer propulsive force, and should be more studied.

Acknowledgments

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