Quantification of swimmers' ability to apply force in the water: the potential role of two new variables during tethered swimming.

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Abstract

This study aimed 1) to examine variables that may quantify the ability to apply force in the water and 2) to test their relationship with free swimming performance. Sixteen regional-level swimmers participated in this study. Average (F_{avg}) and maximum (F_{max}) forces were measured for 30 s arm stroke tethered swimming in a flume at zero and 1.389 m/s water flow speeds. The maximum and average force's relative changes (ΔF_{max} and ΔF_{avg}, respectively) were calculated between tethered swimming at zero and 1.389 m/s water flow speeds. Free swimming speeds were obtained from 25, 50, and 100 m front crawl trials, and were correlated with ΔF_{max} and ΔF_{avg}. A negative correlation was found between ΔF_{max} and 25, 50 and 100 m speeds (r= -0.84, r= -0.74, r= -0.55; p<0.05, respectively) and ΔF_{avg} correlated negatively with 25 and 50 m speeds (r= -0.63, r= -0.54; p<0.05, respectively), but it did not correlate with 100 m swimming speed. The relative change in force could be used to quantify the ability to apply force in the water. This could aid coaches to understand if changes in swimmers' ability to apply force in the water contribute to improvements in performance.

Key words: strength assessment, training, performance testing, sprint, flume

Introduction

Swimmers generate forward displacement using hydrodynamic reaction forces to overcome water resistance (Vorontsov & Rumyantsev, 2000). These reaction forces not only depend on the swimmer's muscular strength production (Keskinen, Tilli, & Komi, 1989), but also on the swimmer's ability to effectively apply that force in the water (Dominguez-Castells, Izquierdo, & Arellano, 2013). A variety of methodologies using different instruments such as linear encoders, load cells and/or pressure plates have been used to assess force in freestyle swimming by testing its relationship with performance in 25 and 50 free (Gatta, Cortesi, Swaine, & Zamparo, 2017; Morouço, Marinho, Keskinen, Badillo, & Marques, 2014) or adapted sprint swimming (Cuenca-Fernández, Gay, Ruiz-Navarro, & Arellano, 2020; Cuenca-Fernández et al., 2020; Dominguez-Castells et al., 2013; Formosa, Toussaint, Mason, & Burkett, 2012). In addition, due to its importance, the number of attempts to measure a swimmer's ability to apply force in the water has recently increased (Morais, Forte, Nevill, Barbosa, & Marinho, 2020; Morouço, Barbosa, Arellano, & Vilas-Boas, 2017; Ruiz-Navarro, Morouço, & Arellano, 2020; Santos, Marinho, Neiva, & Costa, 2021).

Among the experimental methods used to assess forces exerted in the water, tethered swimming is a valid and reliable method (Kjendlie & Thorsvald, 2006; Nagle Zera et al., 2021) because of its specificity to the muscular actions during free swimming (Akis & Orcan, 2004; Amaro, Marinho, Batalha, Marques, & Morouço, 2014). During tethered swimming, force is measured through a transducer fixed to the wall and connected to swimmers' hip by either a non-elastic or elastic tether (Maglischo, Maglischo, Sharp, Zier, & Katz, 1984; Morouço, Keskinen, Vilas-Boas, & Fernandes, 2011), with similar muscular activity (Bollens, E., Annemans, L., Vaes, W., & Clarys, 1988) and stroke and physiological responses to the free swimming (Morouço et al., 2014). Nevertheless, despite tethered swimming being more specific to free swimming than other force measurements, this method disregards water resistive forces (K. B. Dos Santos, Pereira, Papoti, Bento, & Rodacki, 2013) and tends to overestimate the propulsive forces generated by the hand when compared to the free-swimming condition at a sprinting pace (Samson, Monnet, Bernard, Lacouture, & David, 2018). Moreover, the stationary position of the swimmer and unique water flow during tethered swimming may lead to different whole body acceleration and hand trajectories compared to free swimming (Maglischo et al., 1984; Samson et al., 2018). To overcome differences in flow and simulate the displacement of the swimmer, the use of a flume in tethered swimming can be used, producing a state more similar to free swimming than tethered swimming at zero speed (Ruiz-Navarro et al., 2020; Vorontsov, Popov, Binevsky, & Dyrko, 2006).

The correlation between swimming performance and the force in tethered swimming in a flume increases as the water flow speed increases (Ruiz-Navarro et al., 2020; Vorontsov et al., 2006). The magnitude of force in tethered swimming in a stationary position (i.e. zero speed) (Amaro, Morouço, Marques, Fernandes, & Marinho, 2017; Morouço et al., 2011) and in a flume are dependent on muscle strength (Vorontsov et al., 2006); however, the correlation between the force in tethered swimming in a flume and the upper-limbs strength measured in dry-land conditions decreases as the water flow speed increases (Vorontsov et al., 2006). Therefore, it was suggested that these facts were due to the different contributions of the ability to create effective propulsive force (i.e. ability to apply force in the water) in tethered swimming at zero speed and tethered swimming in a flume (Vorontsov et al., 2006). In other words, at zero speed muscle strength has a higher contribution to the magnitude of force, whereas as the speed of the water flow increases, is the ability to apply force in the water which becomes more relevant.

In addition, the correlation between force in tethered swimming at zero speed and in a flume decreased as the water flow increased (Vorontsov et al., 2006), and therefore the same magnitude of force at higher water flow speed may be achieved in two ways: 1) by relying on one’s strength or 2) possessing the ability to effectively apply force. Hypothetically, if swimmer A is stronger than swimmer B, he is likely to achieve a higher magnitude of force in stationary tethered swimming. But swimmer B may be able to apply the same magnitude of force as swimmer A, when swimming at a higher flow speed, because swimmer B has a superior ability to effectively apply force in the water.

Hence, as the magnitude of force in tethered swimming depends on muscle strength and the ability to apply force in the water, it would be of interest for coaches and sports scientists to know the swimmers' ability to apply force regardless of swimmer's muscle strength, since that might contribute to the better understanding of training effects. Therefore, this study aimed 1) to examine variables that can be used to quantify a swimmer's ability to apply force in the water and 2) to test their relationship with free swimming performance. It was hypothesised that the proposed variables would quantify a swimmer's ability to apply force in the water regardless of muscle strength.

Materials and methods

Participants

This study used raw data from the project **"this information was erased from the blind copy to maintaining the anonymity"**. Sixteen Spanish regional male swimmers, from the same squad, provided informed consent to participate in this study (mean ± SD: 19.6 ± 3.3 years of age, 176.1 ± 4.5 cm in height, 70.7 ± 9.5 kg of body mass, 58.24 ± 2.2 s long course 100 m freestyle personal best, FINA points: 528 ± 60 [Performance Level 4 (Ruiz-Navarro, López-Belmonte, Gay, Cuenca-Fernández, & Arellano, 2022)]). Participants were familiar with tethered swimming, had at least five years of competitive swimming experience, and trained four dry-land sessions and six swimming sessions per week with a mean volume of 32 ± 4 Km. The protocol, risk, and benefits of the study were explained to the participants before they provided written consent to participate. Parental swimmers written consent was also requested for swimmers under 18 years old. The study was conducted according to the code of ethics of the World Medical Association (Declaration of Helsinki), and The University of XXXX Ethics Committee approved the protocol (project reference: XXX)

Design

A cross-sectional study design was conducted to test arm stroke tethered forces and free swimming speeds on two consecutive days at the same time of the day. Tethered forces were measured in a swimming flume (Endless Pool Elite Techno Jet Swim 7.5; HP, Aston PA) with a predefined speed range. Swimming time trials for 25, 50, and 100 m, with 20 min of active rest between trials (swimmers conducted their own active rest strategy), were conducted in a 25 m swimming pool. In each session, the tests were preceded by a standardized warm-up. Test order was randomized and performed in identical conditions.

Procedures

The day prior to and on testing days, swimmers were asked to refrain from intense exercise and to avoid the consumption of caffeinated, alcoholic, or stimulant drinks. On day one, before the warm-up, the height and body mass of the swimmers were measured by the same researcher using a stadiometer/scale (Seca 799, Hamburg, Germany). The standardized warm-up, comprised 1000 m low to moderate intensity front crawl swimming (400 m swim, 100 m pull, 100 m kick, 4 × 50 m at increasing speed, 200 m easy swim) (Morouço et al., 2017). Arm stroke tethered swimming was conducted in tethered swimming at zero and at three different water flow speed conditions controlled in a swimming flume: at 0.926, 1.124, and 1.389 m/s speeds of water flow. Nevertheless, only at zero speed and at 1.389 m/s speeds of water flow were used for the current study. Flow speed calibration was conducted before each testing session at 0.30 cm depth using an FP101 flow probe (Global Water, Gold River, CA (McLean, Palmer, Ice, Truijens, & Smith, 2010)) (water temperature = 26°, humidity = 52%). After a pilot study using a variety of flow speeds in the flume, the selected speeds represented 50% of the swimmers' average 100 m maximum speed, average easy swimming speed, and average maximum speed that allows the registration of forces during the entire stroke cycle for a subgroup of participants (n = 4).

Although swimmers were familiar with tethered swimming, they underwent a familiarization protocol with the testing procedures (Psycharakis, Paradisis, & Zacharogiannis, 2011), which consisted of one 15 s submaximal trial at the testing speeds before data collection. Testing comprised 30 s arms-only swimming in the four water flow speeds with 15 min of active rest between each trial. Kick action was restrained to prevent leg movements from interfering with the force measurements (Dominguez-Castells et al., 2013). To avoid the leg kicking restriction that could influence body-roll (Sanders & Psycharakis, 2009), the feet were placed on a support structure that did not interfere with the swimmers' natural body rotation and position. To avoid inertial effects during the first strokes, swimmers swam at a low intensity for 5 s (adapted from Barbosa, Castro, Dopsaj, Cunha, & Júnior, 2013) before a visual-auditory signal indicated the start of the 30 s test to the swimmer. The same signal was used to end the test. Despite the force production is not affected by the breathing actions (Psycharakis, Soultanakis, Gonzalez-Rave, & Paradisis, 2021) swimmers used a snorkel during tethered swimming to avoid any possible disruption as kinematics changes when to breathe or swallow water due to the water flow.

Swimmers were connected by a belt to a load cell (RSCC S-Type; HBM, Darmstadt, Germany) via 2 m steel cable. The load cell was aligned with the direction of swimming (i.e., horizontal), recording at 200 Hz. Analog data were converted (FORCE ISO flex; Remberg, Lasarte-Oria, Spain), registered, and exported (NIUSB600; National Instruments, Austin, TX) to a runtime environment developed using LabVIEW (National Instruments), which allowed visualization of the recordings in real time. The force-time curves were smoothed using a fourth-order Butterworth low-pass digital filter, with a cut-off frequency of 10 Hz.

Swimming performance was measured in a 25 m swimming pool (25 × 16.5 m, water temperature = 27°, humidity = 65%); mean swimming speeds were calculated for 25, 50, and 100 m front crawl, with in-water starts to avoid the effects of the dive on the measurements. Swimmers were asked to start swimming as soon as possible to avoid effects of the underwater phase after the in-water start and turns. Swimming speed was measured as the distance divided by the time for each time trial. Time was measured using Automatic Swimming Performance Analysis (project reference IE_57161), which allowed the automatic collection of performance data from video frames. Technical details were previously provided (Arellano et al., 2018).

Maximum force (F_{max}), which represented the highest value obtained within the 30 s test, and average force (F_{avg}), representing the mean force recorded during the 30 s test, from the force–time curves at zero and 1.389 m/s water flow speeds were analyzed. The force-time curve at 1.389 m/s water flow speed was chosen because it was the maximal speed in our sample and therefore, the condition that the ability to apply force in the water was more manifested.

The reduction of the magnitude between tethered swimming conditions was different among the swimmers. Thus, since swimmers were asked to provide their maximum effort in every swimming condition, then the reduction of the magnitude among conditions should be due to swimmers' ability to apply force in the water. Therefore, the absolute values of the relative change in F_{max} and F_{avg} (equations 1 and 2, respectively) between tethered swimming conditions were calculated as the variables to quantify swimmers' ability to apply force in the water.

$$\Delta F_{max} = \left| \frac{F_{max1.389} - F_{max0}}{F_{max0}} \right| * 100 \qquad \text{Equation 1}$$

Where ΔF_{max} was the maximum force's relative change between tethered swimming conditions, F_{max0} was the maximum force at zero, and $F_{max1.389}$ was the maximum force at 1.389 m/s water flow speed.

$$\Delta F_{avg} = \left| \frac{F_{avg1.389} - F_{avg0}}{F_{avg0}} \right| * 100 \qquad \text{Equation 2}$$

Where ΔF_{avg} was the average force's relative change between tethered swimming conditions, F_{avg0} was the average force at zero, and $F_{avg1.389}$ was the average force at 1.389 m/s water flow speed.

Statistical analyses

Shapiro-Wilk testing indicated all data were normally distributed; therefore, parametric testing was used. Mean and standard deviation were calculated for F_{max} and F_{avg} at zero and 1.389 m/s water flow speeds, respectively; average swimming speed for each time trial; ΔF_{max} and ΔF_{avg}. To evaluate the reduction of the magnitude among maximum and average values, the differences between ΔF_{max} and ΔF_{avg} were tested using a paired sample *t*-test. Cohen's *d* effect size was calculated in Excel 2011 (Microsoft Corporation, Redmond, WA, USA) with the following criteria: 0 to 0.19 trivial, 0.20 to 0.59 small, 0.60 to 1.19 moderate, 1.20 to 1.99 large, 2.00 to 3.90 very large and > 4.00 nearly perfect (Hopkins, 2002). The relationships between swimming performance (i.e., mean speed in the 25, 50, and 100 m trials) and ΔF_{max} and ΔF_{avg} were examined using Pearson's product moment correlation. Confidence intervals (95%), were calculated in Excel as explained by Field (2009) and the following criteria were used to qualitatively assess the correlations: < 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 (Hopkins, 2002). Apart from effects sizes and confidence intervals, the statistical procedures were performed using SPSS (version 24.0; Chicago, IL), with a level of significance set to $p < 0.05$.

Results

Table 1 includes descriptive statistics for the force variables at zero and 1.389 m/s water flow speeds, mean free swimming speed during the time trials, and ΔF_{max} and ΔF_{avg}. ΔF_{max} was significantly smaller than ΔF_{avg} ($p<0.001$; mean difference: 13.72; 95%CI = 10.10 to 17.35; d = 2.02).

(Please insert Table 1 near here)

The ΔF_{max} showed a very large negative correlation with 25 and 50 m ($p<0.001$ and $p<0.01$, respectively) and a large negative correlation with 100 m swimming speed ($p<0.05$) (Figure 1). The ΔF_{avg} presented a large negative correlation with 25 and 50 m swimming speeds ($p<0.05$), and a moderate non-significant negative correlation with 100 m swimming speed (Table 2, Figure 1).

(Please insert Table 2 near here)

(Please insert Figure 1 near here)

Discussion and implications

The aims of this study were to examine variables that could be used to quantify a swimmer's ability to apply force in the water and to test their relationship with free swimming performance.

Both ΔF_{max} and ΔF_{avg} showed large to very large negative correlation with 25, 50, and 100 m free swimming speeds (except for ΔF_{avg} and 100 m free swimming speed).

The magnitude of the propulsive force depends on swimmers' muscular strength production and ability to effectively apply that force in the water (Dominguez-Castells et al., 2013; Keskinen et al., 1989). During tethered swimming, both the ability to apply force in the water and muscle strength are manifested (Gatta et al., 2017); however tethered swimming at zero speed mostly indicates the swimmer's strength potential (Vorontsov et al., 2006), whereas, in the flume, as the water flow approaches to free swimming speed the perception of the ability to apply force in the water is better than at zero speed (Ruiz-Navarro et al., 2020; Vorontsov et al., 2006). Thus, assuming that the swimmers' ability to apply the force in the water was likely the main difference that led to the different magnitude reduction between swimmers, the relative change of tethered swimming force between conditions might be used as a variable to quantify swimmers' ability to apply force in the water regardless of their muscle strength.

Our results showed large to very large negative correlations between both ΔF_{max} and ΔF_{avg} and free swimming performance (except for ΔF_{avg} and 100 m free swimming speed), which means that the lower the ΔF_{max} and ΔF_{avg} (i.e. the lower force reduction between conditions), the higher the free swimming speed (Table 2). The contribution of aerobic and anaerobic sources depends basically upon the duration of the exercise, and therefore on the distance swum (Zamparo, Capelli, & Pendergast, 2011), so it was expected that the relationship decreased as the swimming distance increased (Amaro et al., 2017). In fact, 30 s arm-stroke tethered swimming seems to replicate the effort in 50 m (Ruiz-Navarro et al., 2020), since it is approximately the time required to cover that distance; however, the physiological (Zamparo et al., 2011) and biomechanical (Andersen, Sinclair, McCabe, & Sanders, 2020) differences between distances likely affect this relationship. Thus, combining biomechanical and physiological measurements would aid to understand this phenomenon providing an interdisciplinary approach (Glazier, 2017).

Previous studies performing 30 s tethered swimming at zero speed obtained stronger correlations between 25, 50, 100, and 200 m front crawl swimming performance and average force rather than maximum force (Morouço et al., 2014; Morouço et al., 2011; Ruiz-Navarro et al., 2020). Nevertheless, maximum force appears to be better associated with free swimming performance as the water flow speed increases in a flume (Ruiz-Navarro et al., 2020). In the current study it was observed that ΔF_{max} presented negative correlations with free swimming performance with more swimming tests than ΔF_{avg}. This might be explained because the stroke rate is different between 25, 50, and 100 m (Ruiz-Navarro et al., 2020) and as the stroke rate increases the angle of attack in the push phase changes, causing a decrease in the mean hand propulsive force, which likely affected the correlation between performance and ΔF_{avg} (Koga et al., 2020). Thus, this could indicate that the ability to effectively apply maximum force is more related to sprint swimming performance rather than the capacity to yield high mean force. Therefore, ΔF_{max} might be more suitable to be used when assessing sprint swimming performance than ΔF_{avg}.

To improve swimming performance, swimmers need to improve their ability to effectively use muscular force production in the water (Amaro et al., 2017; Keskinen et al., 1989). Thus, based on our results, a swimmer should try to focus on reducing ΔF_{max} rather than increasing their force values in tethered swimming at zero speed. Since it is crucial to understand the effects of training on performance (Ruiz-Navarro et al., 2021), future studies should aim to analyze the effect of a training period assessing the force and relative changes variables. This might lead to better understand if the changes induced by the training were a consequence of a better ability to apply force in the water. Moreover, ΔF_{max} was significantly smaller than the ΔF_{avg}

(mean difference: 13.72, $p<0.001$). This difference was indeed expected as the increase in water flow speed evoked a different reduction in maximum force (from 214.58 at zero to 110.11 N at 1.389 m/s), compared to average force (from 93.20 at zero to 35.90 N at 1.389 m/s) (Table 1). Knowing how the active drag behaved during the arm stroke cycle in the different tethered swimming conditions, could aid to better understand the different reduction evidenced in maximum and average values.

The main limitation of the current work was that results were under the assumption that the swimmer's ability to apply force in the water was likely the only cause that led to the different magnitude reduction between swimmers. Ruiz-Navarro et al., (2020) showed no differences in stroke rate among tethered swimming at zero speed and in a flume, hence, future studies could be required to find other different causes that might influence the magnitude reduction between swimmers. Despite tethered swimming being a reliable methodology, the reliability has not been confirmed in a flume, which might affect the outcome. It is worth noting that the fact that kicking action was restricted, while tethered swimming, was a limitation that may have affected the association presented in here, underestimating the actual relationship between force variables and swimming performance; however, the restriction allowed more accurate results, avoiding interference of leg movements (Dominguez-Castells et al., 2013). Conducting the measurements in a 25 m swimming pool may have affected the relationships observed for 50 and 100 m swimming speeds since tumble turn ability could have affected the final outcomes obtained in these distances (Veiga, Roig, & Gómez-Ruano, 2016). Therefore, in terms of assessing free swimming speed a 50 m swimming pool could be more appropriate. In addition, it is not so common to have a swimming flume available; in this regard, future experiments could be performed in a swimming pool by assessing the ability to develop effective force in the water while full and semi-tethered tests (e.g., the relative change between the force obtained in fully tethered swimming and the force obtained in semi-tethered swimming on a power rack displacing a load).

Conclusion

The findings of this study show that the maximum and average force's relative changes between arm stroke tethered swimming at zero (i.e., full tethered swimming) and 1.389 m/s water flow speeds could be used to quantify swimmers' ability to apply force in the water regardless of their muscle strength. Higher values of ΔF_{max} and ΔF_{avg} were related to lower swimming speed, which could lead coaches to focus on improving swimmers' skills rather than increasing physical conditioning. Furthermore, coaches could assess swimmers before and after periods of training and detect the effects on swimmers' ability to apply force. Therefore, coaches can use the techniques presented here to better understand the effects of their training on swimmers' performance variations.

Disclosure Statement:

The authors have no conflicts of interest to report.

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Table and figure captions:

Table 1. Mean ± SD Values for the tethered swimming grouped by water-flow speeds, free swimming performances, and relative changes.

Table 2. Pearson correlations with 95% confidence intervals between the relative changes and free swimming performance.

Figure 1. Scatter plots showing the Pearson correlations between 25, 50 and 100 m free swimming speed and maximum force's relative change (left column) and average force's relative change (right column). Individual value and 95% confidence lines are represented. ΔF_{max} indicates maximum force's relative change; ΔF_{avg} average force's relative change; V25m, speed in 25 m; V50m, speed in 50 m; V100m, speed in 100 m.

Table 1. Mean ± SD Values for the tethered swimming grouped by water-flow speeds, free swimming performances, and relative changes.

Water flow speed: 0-m/s		Water flow speed : 1.389- m/s		Free swimming			Relative change	
F_{max} (N)	F_{avg} (N)	F_{max} (N)	F_{avg} (N)	SV25m (m/s)	SV50m (m/s)	SV100m (m/s)	ΔF_{max} (%)	ΔF_{avg} (%)
214.58 ± 48.66	93.20 ± 16.92	110.11 ± 36.18	35.49 ± 15.23	1.84 ± 0.05	1.80 ± 0.06	1.66 ± 0.06	49.23 ± 10.25	62.96 ± 11.86

F_{max}, maximum force
F_{avg}, average force
ΔF_{max}, maximum force's relative change
ΔF_{avg}, average force's relative change
SV25m, swimming speed in 25 m
SV50m, swimming speed in 50 m
SV100m, swimming speed in 100 m

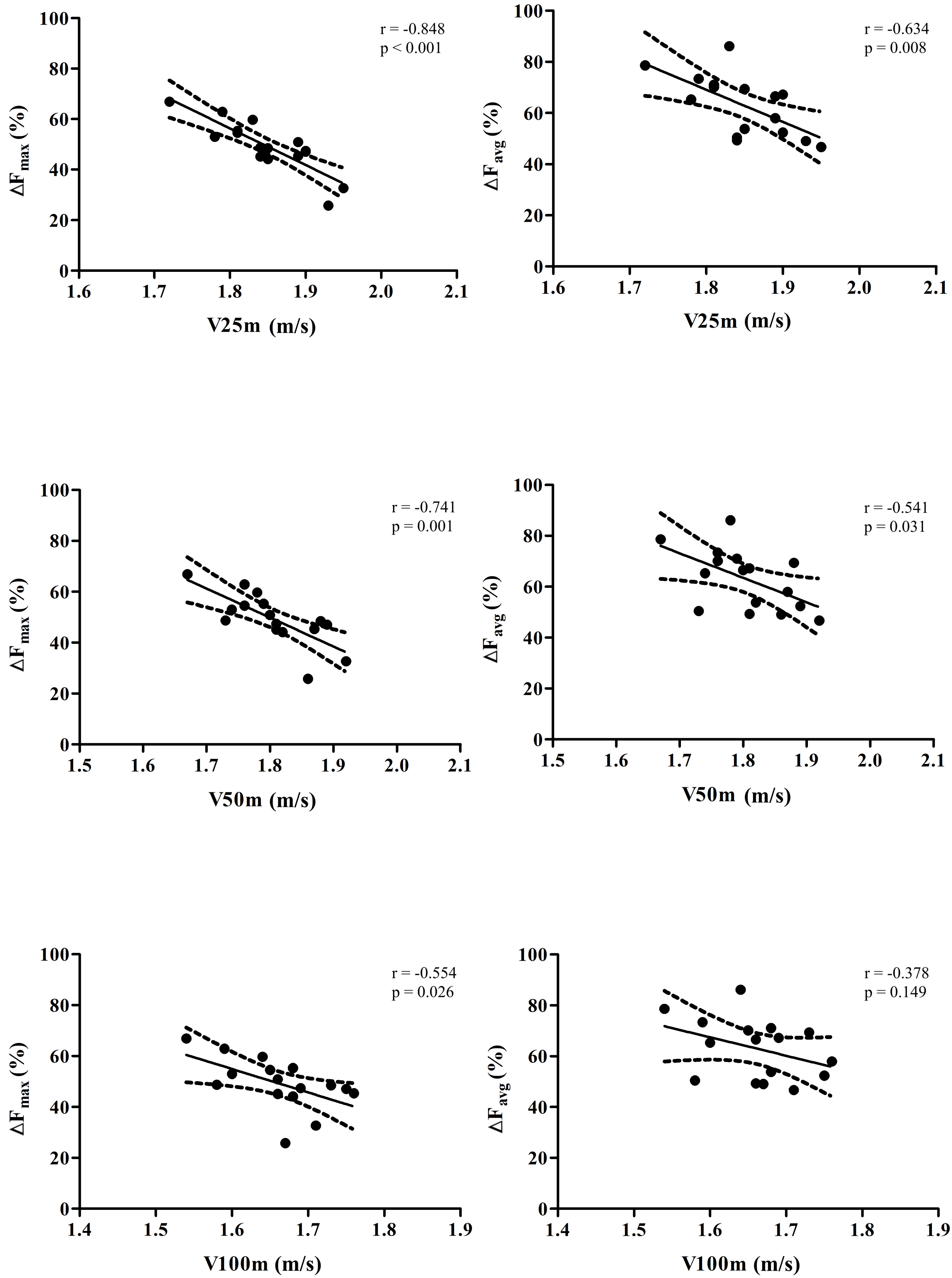
Table 2. Pearson correlations with 95% confidence intervals between the relative changes and free swimming performance.

	ΔF_{max} (%)	ΔF_{avg} (%)
	Pearson (*r*) [95%CI]	Pearson (*r*) [95%CI]
SV25m (m/s)	-0.848*** [-0.946, -0.608]	-0.634** [-0.860, -0.202]
SV50m (m/s)	-0.741** [-0.904, .0.388]	-0.541* [-0.817, -0.062]
SV100m (m/s)	-0.554* [-0.819, -0.066]	-0.378 [-0.736, 0.145]

ΔF_{max}, maximum force's relative change
ΔF_{avg}, average force's relative change

SV25m, mean swimming speed in 25 m front crawl
SV50m, mean swimming speed in 50 m front crawl
SV100m, mean swimming speed in 100 m front crawl

* p<0.05
**p<0.01
***p<0.001


r = -0.848
p < 0.001
ΔFmax (%)
V25m (m/s)
r = -0.634
p = 0.008
ΔFavg (%)
V25m (m/s)
r = -0.741
p = 0.001
ΔFmax (%)
V50m (m/s)
r = -0.541
p = 0.031
ΔFavg (%)
V50m (m/s)
r = -0.554
p = 0.026
ΔFmax (%)
V100m (m/s)
r = -0.378
p = 0.149
ΔFavg (%)
V100m (m/s)