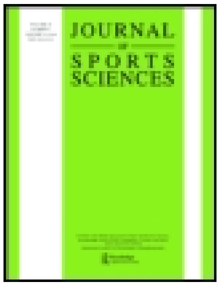

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Acute responses of biomechanical parameters to different sizes of hand paddles in front-crawl stroke

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Abstract
This study investigated the acute effects of different sizes of paddles on the force-time curve during tethered swimming and swimming velocity in front-crawl stroke. Fourteen male swimmers (20.0 ± 3.7 years; 100-m best time: 53.70 ± 0.87 s) performed two 10-s maximal efforts in tethered swimming to obtain peak force, average force, impulse, rate of force development, stroke duration and time to peak force. Swimming velocity, stroke rate and stroke length were obtained from two 25-m maximal swims. Both tests were repeated in five conditions: free swimming, wearing small (280 cm^2), medium (352 cm^2), large (462 cm^2) and extra-large (552 cm^2) hand paddles. Compared to free swimming, paddles provided significant increases of peak force (medium: 11.5%, large: 16.7%, extra-large: 21.7%), impulse (medium: 15.2%, large: 22.4%, extra-large: 30.9%), average force (medium: 5.1%, large: 7.5%), rate of force development (extra-large: 11.3%), stroke duration (medium: 9.3%, large: 11.8%, extra-large: 18.5%), time to peak force (medium: 11.1%, large: 15.9%, extra-large: 22.1%), swimming velocity (medium: 2.2%, large: 3.2%, extra-large: 3.7%) and stroke length (medium: 9.0%, large: 9.0%, extra-large: 14.8%), while stroke rate decreased (medium: –6.2%, large: –5.5%, extra-large: –9.5%). It is concluded that medium, large and extra-large paddles influence the force-time curve and change swimming velocity, suggesting these sizes may be useful for force development in water.

Keywords: *hand paddles, swimming, propulsive force, velocity, tethered swimming*

Introduction

Propulsive force plays an important role in swimming performance development (Rasulbekov, Fomin, Chulkov, & Chudovsky, 1986; Toussaint, Hollander, Van den Berg, & Vorontsov, 2000). It results from the interaction between swimmers' limbs and water, and can be decomposed into drag and lift forces, described by the following equations, according to hydrodynamic theory (Toussaint et al., 2000):

$$D = 1/2 \cdot \rho \cdot C_D \cdot S \cdot v^2 \quad (1)$$
$$L = 1/2 \cdot \rho \cdot C_L \cdot S \cdot v^2 \quad (2)$$

Where ρ is the water density, C_D and C_L are drag and lift coefficients, respectively, v is the hand velocity and S the hand surface. An optimal combination of these forces is crucial to generate a resultant force in the forward direction (Schleihauf, 2004).

One of the most used methods for resultant force evaluation is fully tethered swimming (Dopsaj, Matković, & Zdravković, 2000) in which the swimmers perform the sport-specific actions connected by an inextensible cable to a force transducer (Castro, Oliveira, Moré, & Mota, 2010). Although the zero velocity imposed by this method can change the speed and trajectory of the propulsive segments (Maglischo, Maglischo, Sharp, Zier, & Katz, 1984), it is generally assumed to be sport-specific due to its metabolic and electromyographic similarities with non-tethered swimming (Bollens, Annemans, Vaes & Clarys, 1988; Bonen, Wilson, Yarkony, & Belcastro, 1980; Cabri, Annemans, Clarys, Bollens, & Publie, 1988; Holmer, 1979) and sensitivity regarding the identification and monitoring of training-induced adaptations as well (Papoti, Martins, Cunha, Zagatto, & Gobatto, 2007).

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Over the years, different means of training have been considered as possibilities to enhance the resultant force (Girold, Calmels, Maurin, Milhau, & Chatard, 2006; Gourgoulis, Aggeloussis, Vezos, & Mavromatis, 2006; Gourgoulis, Aggeloussis, Vezos, Kasimatis, Antoniou, & Mavromatis, 2008; Gourgoulis, Aggeloussis, Vezos, Antoniou, & Mavromatis, 2008; Mavridis, Kabitsis, Gourgoulis, & Toubekis, 2006; Telles, Barbosa, Campos, & Andries Júnior, 2011; Toussaint & Vervoorn, 1990) and because the arms produce approximately 85% of the propulsion in front-crawl stroke (Toussaint et al., 2000) most of the training is dedicated to developing the upper limb strength.

In water, hand paddles are possibly the most used implement for this purpose. Through them, swimmers experience an artificial enlargement of their hands that allows pushing off against a bigger mass of water and, consequently, a greater drag should be overcome in each stroke (Toussaint, Janssen, & Kluft, 1991). In fact, Gourgoulis, Aggeloussis, Vezos, Kasimatis et al. (2008) showed that these implements cause a significant increase in hand lift and drag forces without changing their relative contribution for propulsion or the resultant force direction. The authors also noticed that these results change according to the paddle size (Gourgoulis, Aggeloussis, Vezos, Kasimatis, et al., 2008). Then, hypothetically, as the paddle surface increases, a greater stroke propulsive force is generated.

In this sense, it is important to consider that the increase of resistance to overcome also implies a significant reduction of hand velocity (Gourgoulis et al., 2006; Gourgoulis, Aggeloussis, Vezos, Kasimatis, et al., 2008; Gourgoulis, Aggeloussis, Vezos, Antoniou, et al., 2008) and, therefore, to observe an increase of propulsive force, the effect of hand enlargement (i.e. S) should compensate the decrease of v, even though mathematically it has a greater effect due to its quadratic relation.

As shown by Gourgoulis, Aggeloussis, Vezos, Kasimatis et al. (2008), this compensatory-mechanism does work for female swimmers wearing paddles of 116 and 268 cm^2. Considering these sizes are smaller or similar to the men's hand area previously estimated (201.15 ± 33.70 cm^2) (Telles et al., 2011) and also that men's capacity to produce propulsive force is admittedly higher than women's (Adams, Martin, Yeater, & Gilson, 1983), a larger size would be required to provide significant changes to a male swimmer's propulsive force. Nevertheless, it is still unknown whether the mechanism would be reproduced in this condition.

Therefore, the main aim of the current investigation was to examine the acute responses of the tethered force-time curve and swimming velocity to four different sizes of paddles (280, 352, 462 and 552 cm^2) in competitive front-crawl male swimmers (tethered force was assumed to represent the propulsive force generated by the swimmers). It is our hypothesis that the propulsive force and swimming velocity increase in association with the enlargement of the surface area.

Methodology

Participants

Fourteen well-trained male swimmers took part in this study (age: 20.0 ± 3.7 years; body mass: 76.3 ± 8.6 kg; fat percentage: 8.6 ± 2.6%; height: 1.84 ± 0.08 m; arm span: 1.88 ± 0.09 m; percentage from the 100-m freestyle world record: 87.4 ± 1.4%). To be included, each participant had to be national competitive in 50-m, 100-m and/or 200-m freestyle, have at least four years of competitive experience (9.0 ± 4.4 years) and a minimum of two years of training with paddles (7.3 ± 3.1 years). These criteria were adopted to avoid the inclusion of inexperienced swimmers. Written consent was obtained and all the procedures received approval from the university's ethics committee where this study was carried out.

Experimental procedures

Tests were performed in the week after the main competition of the season using the front-crawl stroke. The water temperature was 27 ± 1°C. As a standardised warm-up, swimmers performed a 10-minute self-stretching, 10 minutes of free swimming and also four 15 m sprints 90 seconds apart. Five minutes were given before the beginning of the tests.

During the same day swimmers reported to the pool in two sessions. In the first, propulsive force was tested during a maximal 10-second protocol in the fully tethered swimming. In the second, swimming velocity, stroke rate and stroke length were analysed in 25-m maximal sprints. The tests were repeated five times to reproduce the following conditions: free swimming (hand area = mean: 233.7 cm^2; s: 32.9 cm^2; maximum: 281.3 cm^2; minimum: 185.3 cm^2), with small (280 cm^2), medium (352 cm^2), large (462 cm^2) and extra-large hand paddles (552 cm^2), as shown in Figure 1. The shape and sizes of paddles are shown in Figure 2. Swimmers were familiar with different sizes of paddles, which were regularly used during their training sessions.

The surface areas of hands and paddles were estimated by multiplying distances between their extreme transverse and longitudinal points, as used previously (Telles et al., 2011). Two adjustable elastic straps around the middle finger and wrist fastened the paddles to the hand.

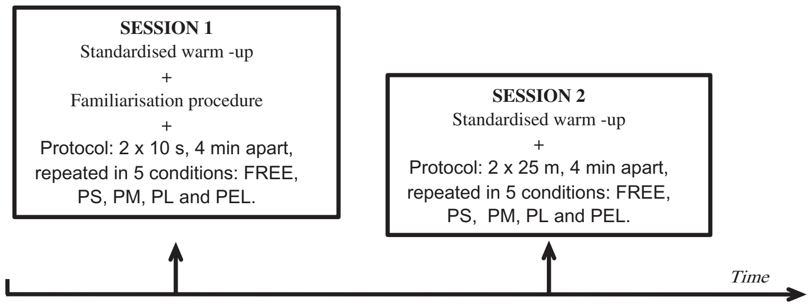

Figure 1. Experimental design. FREE = free swimming, PS = small, PM = medium, PL = large and PEL = extra-large hand paddles.

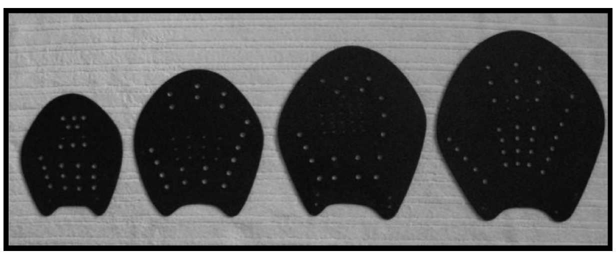

Figure 2. Shape and sizes of the hand paddles tested.

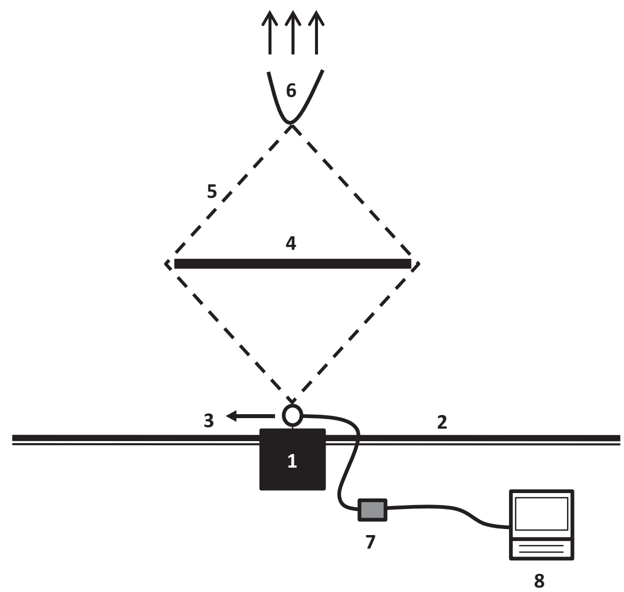

Figure 3. Top view of the tethered swimming: (1) starting platform, (2) wall, (3) load cell, (4) floating bar, (5) inextensible cables, (6) belt, (7) interface and (8) computer. Swimmers were instructed to swim according to the arrows' direction.

Propulsive force

The tethered swimming system (CEFISE, Nova Odessa, Brazil) consisted of a load cell with four strain gauges, 2000 N of maximum capacity and 30 g of maximum resolution. One of its extremities was fixed to a specially-designed support, attached to the starting platform, while the other was connected to an inextensible cable system, in which the swimmer was tethered on the waist through an adjustable belt (Figure 3).

Mechanical deformations in the load cell generated by swimmers' propulsive forces during the test protocol were recognised by an analogue/digital (A/D) interface, which converted the analogue voltage into a digital signal. The data were stored in a data acquisition program at 600 Hz. Raw data were smoothed using a fourth-order Butterworth low pass digital filter (Papoti, Martins, Cunha, Zagatto, & Gobatto, 2003). The cut-off frequency of 8 Hz was determined through residual analysis (Winter, 1990). The system was calibrated using increments of 20 kg to the maximum weight of 100 kg and the force values were obtained through the linear regression line ($r^2 = 1.00$, $P < 0.0001$). Prior to the testing session, the calibration was checked using an arbitrary weight of 9.4 kg.

Even though most of the swimmers were familiar with the equipment, a specific procedure was conducted for familiarisation. It consisted of one 10-second trial at medium intensity, which could be repeated until participants felt themselves comfortable.

The test protocol consisted of two 10-second maximal swims with four minutes of rest, adopted to prevent possible effects of fatigue. The beginning (after approximately five seconds of moderate swimming) and the end of the test protocol were signalled by a whistle. In order to minimise the effects of swimming intensity transition, which can overestimate the real force values, one second was given between the whistle and the start of data acquisition, as adopted in previous investigations (Papoti et al., 2003; Trappe, Costill, & Thomas, 2001).

During the test, swimmers were requested to hold their breath to avoid major modifications of stroke kinematic (Gourgoulis, Aggeloussis, Vezos, Antoniou, et al., 2008). Leg kick was allowed in an attempt to keep the whole stroke technique closer to that normally used in non-tethered swimming. As maximum intensity was required, their contribution for propulsion was assumed to be similar in all conditions. The cycle frequency was self-chosen. A

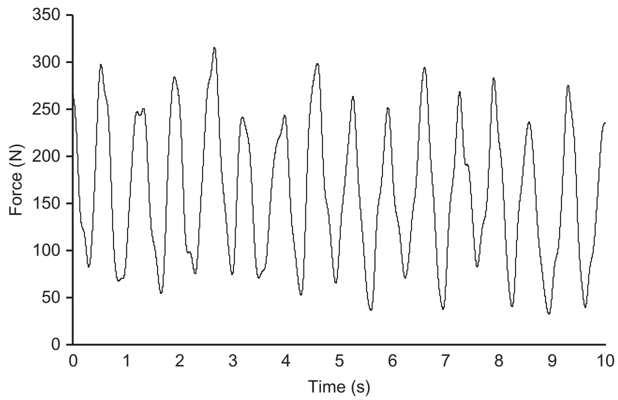

Figure 4. Typical filtered front-crawl stroke force-time curve during a 10-second test.

typical filtered force-time curve obtained in a 10-second test protocol is shown in Figure 4. Each peak was assumed to represent predominantly the propulsive force of one arm.

The test protocol was repeated five times in the following conditions: (1) free swimming, (2) with small, (3) medium, (4) large and (5) extra-large hand paddles. The order of the conditions was randomised. The rest between them lasted approximately 5 min (2 min active + 3 min passive), adopted with the intent of attenuating any possible effect of the previous conditions on swimmers' stroke sensitivity.

In each trial, eight consecutive strokes were analysed through the procedures previously described (Dopsaj et al., 2000). The main points of the force-time curve (Figure 5) were marked in each arm stroke for the assessment of the following parameters:

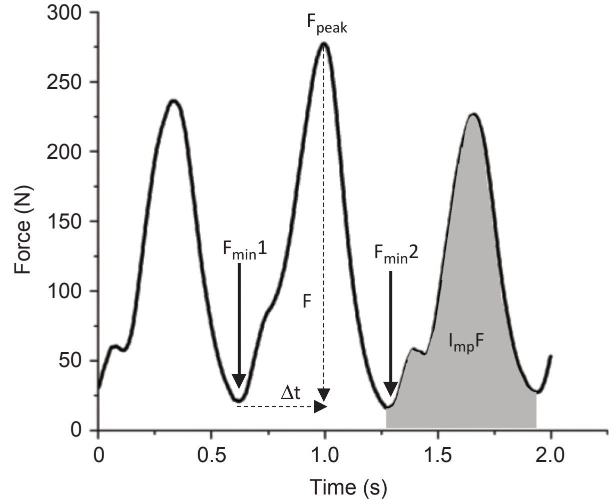

Figure 5. Determinant instants used for force-time curve analysis. F_{peak} = Peak force; $I_{mp}F$ = impulse, represented by the curve's area; $F_{min}1$ = beginning of the stroke; $F_{min}2$ = end of the stroke; Δt = time variation; ΔF = force variation.

1. Peak force (F_{peak}): the maximum force value found in one arm stroke, expressed in N.
2. Average force (F_{avg}): the average of all force values found in one arm stroke, i.e., between minimum force 1 ($F_{min}1$) and 2 ($F_{min}2$), expressed in N.
3. Minimum force ($F_{min}1$): the minimum force value between two force peaks, expressed in N. This parameter resulted from a recognised intracyclic force variation (Keskinen & Komi, 1993) and was assumed as the beginning of one stroke and the end of the previous one. Although superposition coordination might be found during this test, it generally lasts only about 3% of the duration of a complete stroke in swimmers with a similar competitive level (Millet, Chollet, Challis, & Chatard, 2002; Seifert, Chollet, & Bardy, 2004; Seifert, Chollet, & Rouard, 2007). Therefore, the force values found between two minimum force points were attributed predominantly to the action of one arm. It is reasonable since minimum force presents an acceptable reliability (intraclass coefficient correlation: 0.92; 95% confidence interval: 0.78–0.97; intermeasure coefficient of variation 10.3%; standard error of measurement: 2.03 N), as shown previously (Barbosa, Maciel, Moreira, Serrão, & Andries Júnior, 2012).
4. Stroke Duration (DUR): time difference between the instants $F_{min}2$ and $F_{min}1$, expressed in milliseconds.
5. Time to peak force (TF_{peak}): time difference between $F_{min}1$ and F_{peak} (Δt), expressed in milliseconds.
6. Rate of force development (RFD): the ratio between force variation ($\Delta F = F_{peak} - F_{min}1$), expressed in N, and the time to peak force (TF_{peak}), expressed in milliseconds, according to: $RFD = (\Delta F/TF_{peak}) \times 1000$. RFD was expressed as $N \cdot s^{-1}$.
7. Impulse ($I_{mp}F$): the force applied in a given time. In this case, $I_{mp}F = F_{avg} \cdot DUR$. It is represented by the area under the force-time curve and expressed in N · s. Integration was carried out using the trapezoidal method.

This analysis of the force-time curve was repeated for the two efforts performed and the average value of the 16 arm actions analysed (i.e. eight in each trial) was retained for analysis.

Swimming velocity

Swimming velocity was measured according to the procedure described by Telles et al. (2011). The test consisted of two 25-metre maximal swims with four minutes of rest. Swimmers were requested to hold

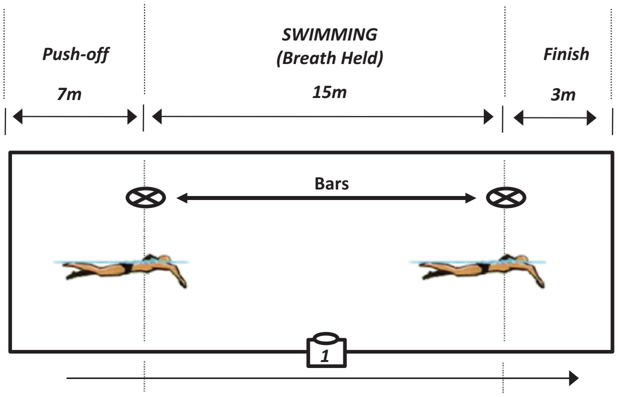

Figure 6. Test description: 1 = moving underwater camera.

their breath during the whole distance covered to avoid any modifications of stroke kinematic (Gourgoulis, Aggeloussis, Vezos, Antoniou, et al., 2008). In order to minimise the effects of push-off and finish the first seven and the last three metres were discarded. For this, two vertical underwater bars were positioned 15-m apart, perpendicularly to the swimmer's displacement at the distances of 7 and 22-m from the pool edge (Figure 6).

The trials of each swimmer were filmed by one Mini DV camera (Sony® HC38, shutter speed: 1/250, sampling frequency: 60 Hz) placed underwater with the aid of a waterproof box (Sony® SPK-HCC) at a depth of 50 cm. It filmed the swimmer's motion from a sagittal view with the aid of a trolley, which was pulled alongside the pool by an operator, at the same velocity as the swimmer. The swimmer's head was the mark followed by the trolley's operator.

The videos were analysed and the frames in which the swimmer's head crossed the bars were identified. Swimming velocity (VEL) was calculated by dividing the known distance (15 m) by the time spent between the bars (Δt) according to: VEL = $15/\Delta t$, with an accuracy of 0.016 s and a standard error of measurement of 0.003 $m \cdot s^{-1}$ (Telles et al., 2011).

Stroke rate (SR), expressed in cycles per minute, was quantified by analysing the time of the first four complete cycles performed after the initial 7 m (Δt_2), computed by video analysis, according to: $SR = (60 \star 4)/\Delta t_2$. Stroke length, expressed in metres per cycle, was obtained by the ratio between swimming velocity and stroke rate, converted to cycles per second. From the two efforts the average value was retained for analysis.

The test protocol was repeated five times in the following conditions: (1) free swimming, (2) with small, (3) medium, (4) large and (5) extra-large hand paddles. The order was randomised. The rest between conditions was 100 m swimming freely plus two minutes of passive rest.

Statistical analysis

The assumptions of normally distributed samples and sphericity were verified using Shapiro-Wilk and Mauchly tests, respectively. Repeated measures analysis of variance (ANOVA) computed the possible main effect of the factor 'size of paddles' on all parameters (except stroke duration). If sphericity was violated the P values were adjusted by the epsilon Greenhouse-Geisser correction factor. Multiple pairwise comparisons were made using the Bonferroni test. Due to the non-parametric distribution, stroke duration was treated using Friedman ANOVA. The Wilcoxon test, with the Bonferroni adjustment, was used to detect any possible significant difference. The significance level was set at $P < 0.05$. All data are expressed as means ± standard deviations ($M \pm s$). Analyses were conducted using SPSS for Windows (Version 16.0; SPSS, Inc., Chicago, IL).

Results

Propulsive force

The statistical analysis showed that the factor 'size of paddles' has a significant main effect on peak force ($F_{4,65}$ = 42.666, P <0.0001, eta^2 = 0.766), average force ($F_{4,65}$ = 5.043, P = 0.002, eta^2 = 0.279), minimum force ($F_{4,65}$ = 12.358, P < 0.0001, eta^2 = 0.487), time to peak force ($F_{4,65}$ = 22.971, P <0.0001, eta^2 = 0.639), stroke duration (Chi-square = 48.760; P < 0.0001), rate of force development ($F_{4,65}$ = 3.204, P <0.05, eta^2 = 0.198) and impulse ($F_{4,65}$ = 71.961, P < 0.0001, eta^2 = 0.847). Significance differences in post-hoc comparisons, descriptive statistics of the parameters and percentage differences of the mean from free swimming are shown in Table I.

Swimming velocity

A significant main effect was observed in swimming velocity ($F_{4,65}$ = 18.041, P <0.0001, eta^2 = 0.581). The size of paddles also significantly altered the stroke rate ($F_{4,65}$ = 22.159, P < 0.0001, eta^2 = 0.630), which decreased as the paddle size increased, while the stroke length increased ($F_{4,65}$ = 41.316, P <0.0001, eta^2 = 0.761), as shown in Table II.

Discussion

Propulsive force

The present study showed that medium, large and extra-large hand paddles significantly affect the force-

Table I. Descriptive statistics (M ± *s*) and percentage differences of the mean from free swimming (Δ%) of peak force (F_{peak}, N), average force (F_{avg}, N), minimum force (F_{min}, N), rate of force development (RFD, N · s^{-1}), time to peak force (TF_{peak}, ms), stroke duration (DUR, ms) and impulse ($I_{mp}F$, N · s) in free swimming (FREE) and with small (PS), medium (PM), large (PL) and extra-large hand paddles (PEL).

		Conditions				
		FREE	PS	PM	PL	PEL
F_{peak}	M ± *s*	278 ± 29	293 ± 39	310 ± 36 [a,b]	324 ± 39 [a,b,c]	338 ± 40 [a,b,c,d]
	Δ%	–	5.3%	11.5%	16.7%	21.7%
F_{avg}	M ± *s*	148 ± 10	151 ± 14	156 ± 14 [a]	159 ± 17 [a,b]	156 ± 19
	Δ%	–	1.6%	5.1%	7.5%	5.6%
F_{min}	M ± *s*	49 ± 15	46 ± 13	43 ± 14	42 ± 14	30 ± 11 [a,b,c,d]
	Δ%	–	−7.0%	−11.6%	−14.7%	−38.4%
RFD	M ± *s*	701 ± 86	727 ± 138	731 ± 105	751 ± 117	780 ± 135 [c]
	Δ%	–	3.7%	4.4%	7.1%	11.3%
TF_{peak}	M ± *s*	333 ± 38	348 ± 43	370 ± 37 [a]	386 ± 51 [a,b]	407 ± 55 [a,b,c,d]
	Δ%	–	4.5%	11.1%	15.9%	22.1%
DUR	M ± *s*	655 ± 70	685 ± 78	721 ± 84 [a,b]	750 ± 94 [a,b]	823 ± 127 [a,b,c,d]
	Δ%	–	1.2%	9.3%	11.8%	18.5%
$I_{mp}F$	M ± *s*	97 ± 15	105 ± 21	112 ± 16 [a]	119 ± 17 [a,b,c]	127 ± 20 [a,b,c,d]
	Δ%	–	7.7%	15.2%	22.4%	30.9%

Note: [a] Significantly different from FREE. [b] Significantly different from PS. [c] Significantly different from PM. [d] Significantly different from PL.

Table II. Descriptive statistics (M ± *s*) and percentage differences of the mean from free swimming (Δ%) of swimming velocity (VEL, m · s^{-1}), stroke rate (SR, cycles · min^{-1}) and stroke length (SL, m · $cycle^{-1}$) in free swimming (FREE) and with small (PS), medium (PM), large (PL) and extra-large hand paddles (PEL).

		Conditions				
		FREE	PS	PM	PL	PEL
VEL	M ± *s*	1.85 ± 0.09	1.87 ± 0.09	1.89 ± 0.09 [a]	1.91 ± 0.08 [a,b]	1.92 ± 0.09 [a,b]
	Δ%	–	0.7%	2.2%	3.2%	3.7%
SR	M ± *s*	52.0 ± 3.5	51.8 ± 2.8	48.8 ± 3.3 [a,b]	49.1 ± 3.2 [a,b]	47.0 ± 3.6 [a,b,c]
	Δ%	–	−0.5%	−6.2%	−5.5%	−9.5%
SL	M ± *s*	2.15 ± 0.18	2.17 ± 0.18	2.34 ± 0.20 [a,b]	2.34 ± 0.19 [a,b]	2.46 ± 0.25 [a,b,c,d]
	Δ%	–	1.2%	9.0%	9.0%	14.8%

Note: [a] Significantly different from FREE. [b] Significantly different from PS. [c] Significantly different from PM. [d] Significant different from PL.

time curve of the front-crawl stroke during tethered swimming. Previous studies stated that because of the greater drag to overcome in each stroke (Toussaint et al., 1991) there is a significant decrease in hand velocity (Gourgoulis et al., 2006; Gourgoulis, Aggeloussis, Vezos, Kasimatis, et al., 2008; Gourgoulis, Aggeloussis, Vezos, Antoniou, et al., 2008), and an increase in the time spent in underwater phases, which explains the significant increase in stroke duration in the current investigation.

This result could be expected since the muscles' amount of time to develop force is proportional to the imposed resistance in maximal efforts (Rasulbekov et al., 1986). However, considering that training-induced adaptations are maximised at or near the velocity of training (Kawamori & Newton, 2006), the magnitude of changes in movement speed defines whether the specificity principle is violated or not. Particularly in swimming, a possible predictable chronic effect of the systematic use of large paddles would be a reduction of the swimmer's capacity to produce high hand velocity during conventional swimming. Unfortunately the question about velocity-specificity in water-resisted training is not well stated yet and, therefore, it is still unknown if the increase of the stroke duration occasioned by medium, large and/or extra-large paddles would cause unspecific adaptations or not.

The enlargement of hand surface also affected peak force, which increased significantly as medium, large and extra-large paddles were worn. As known, propulsive force depends on both drag and lift forces, which can be expressed by the equations described in the introduction, according to hydrodynamic theory (Toussaint et al., 2000). If it is assumed that ρ, C_D and C_L are constants, any change in propulsive force would be a consequence of an increase of v and/or S. However, in hand-paddles swimming these parameters (i.e. v and S) are opposites, i.e. there is a significant reduction of hand velocity (Gourgoulis et al., 2006; Gourgoulis, Aggeloussis, Vezos, Kasimatis, et al., 2008; Gourgoulis, Aggeloussis, Vezos, Antoniou, et al., 2008) as the hand surface is increased. Therefore, the significant increases of peak force point out that the effect of hand enlargement compensated the decrease of v, even though mathematically it has a greater effect due to its quadratic relation. These results corroborate those presented by Gourgoulis, Aggeloussis, Vezos, Kasimatis et al. (2008).

On the contrary, when small paddles were worn, there were no significant changes in peak force. One possible explanation is that the increase of the surface was not enough to balance the reduction in hand speed. Additionally, this result can also be due to the lack of convergence of the effects of these sizes in the group. In other words, when a given size of paddles is worn, the propulsive area of the hand becomes equal for all swimmers. Then, at the same hand velocity, those with small hands have a greater percentage increase in resistance to overcome than those who already have a large hand area (i.e. swimmers experience individual changes in the force produced which vary according to the difference between his or her hand area and the paddle size). This suggests that small paddles provide expressive increases in peak force mainly in those swimmers with smaller hands. Moreover, the significant changes found in peak force also confirm that large paddles primarily emphasise an upper force-part of the force-time curve while small paddles influence a lower portion of the curve.

Additionally, the force increment throughout the stroke compensated the increase of its duration and therefore significant changes were detected in the average force with medium and large paddles. The same result might be expected for the extra-large size, but despite enabling the highest force production amongst the sizes, it also caused the greatest augmentation in the stroke duration and therefore no changes could be detected.

The same principle can be applied for the rate of force development, which is dependent on both force variation and time to reach the peak force. Particularly in the extra-large paddle size, in which significant improvements were detected, time to peak force was influenced by the greater peak force and also by the lower minimum force, which was reduced significantly.

Changes in minimum force can also point to possible changes in the stroke coordination pattern (i.e., the lag time between the beginning of propulsion of one arm and the end of propulsion of the other). This possible change in the coordination mode in overloaded swimming was already noticed by previous studies. Telles et al. (2011) showed the index of coordination changed from catch-up to opposition when paddles of 462 cm^2 were used. Similarly, Sidney, Paillette, Hespel, Chollet, and Pelayo (2001) found a significant increase of the index of coordination when paddles (360 cm^2) were worn. These results might not be in accordance with those shown in the present study. Differently, Gourgoulis, Aggeloussis, Kasimatis, Vezos, Antoniou, and Mavromatis (2009) reported that arm coordination of front-crawl female swimmers remained practically unchanged in catch-up mode when hand paddles were worn. The problem is that front-crawl coordination is significantly influenced by the factor 'gender' (Seifert et al., 2007) and the participants analysed in the present study were males. Indeed, this significant decrease of the minimum force evidenced a greater intracyclic force variation, which may result from a recognised smaller push phase in tethered swimming (Maglischo et al., 1984). This would possibly cause an increase of the lag time between the beginning of propulsion of one arm and the end of propulsion of the other in tethered conditions.

Significant changes were also detected in the impulse. According to Dopsaj et al. (2000), it defines the swimmer's working potential to be performed in non-tethered conditions and has been considered in different models of swimming performance prediction, independently of swimmers' level and/or stroke (Barbosa, Dopsaj, Okicic, & Andries Júnior, 2010; Castro et al., 2010; Dopsaj et al., 2000; Papoti et al., 2003). According to these models, the increase of impulse is significantly related to the increase of swimming velocity. Hence, these significant increases of impulse occasioned by medium, large and extra-large sizes suggest that they can be useful for propulsive force development, as a specific strength conditioning exercise in the water, and also that the different sizes may lead to effects of different magnitudes.

Additionally, the impulse as represented by the force-time curve area can be basically affected by its height, base and inclination, which are respectively related to peak force, stroke duration and rate of force development. Indeed, the significant changes observed in all of these parameters reinforce that medium, large and extra-large hand paddles can be useful for propulsive force development (i.e. increase the impulse).

The question which arises from this discussion is: will this be completely transferred to regular swimming conditions? In fact, these results should be interpreted considering the limitations of tethered swimming. Despite being a sport-specific device to simulate swimming characteristics with respect to environmental, physiological (Bonen et al., 1980) and neuromuscular aspects (Bollens et al., 1988; Cabri et al., 1988; Holmér, 1979), and also being sensitive to the training-induced adaptations (Papoti et al., 2007), it does not represent exactly the conditions of free swimming, as will be discussed later.

Swimming velocity

Similar to propulsive force, significant changes were observed in swimming velocity, stroke rate and stroke length when medium, large and extra-large paddles were worn. As the paddle size increased, there was a greater resistance and to overcome it, a greater propulsive force should be generated by the neuromuscular system. As this process does not happen instantaneously (Rasulbekov et al., 1986), there was a gradual decrease of the stroke rate throughout the sizes, which became significant from the medium size onwards.

As known, swimming velocity is the product of stroke rate and stroke length, parameters traditionally recognised by their inverse relation (Craig & Pendergast, 1979). Considering the stroke rate reduction as a consequence of overloaded swimming, positive changes in swimming velocity would be dependent of a disproportional increase of the stroke length, which actually happened. Stroke rate reduction reached 6.2, 5.5 and 9.5% when medium, large and extra-large paddles were worn, respectively, while stroke length increased 9.0, 9.0 and 14.8%, respectively.

The significant increase of the propulsive force (represented by peak force and impulse), generated by the artificial hand surface enlargement, provided to swimmers a greater displacement per stroke, which may be related to an increase in propelling efficiency (Toussaint et al., 1991). However, it should be noted that the percentage variations of propulsive force were greater than those found in the stroke length. According to Pessôa-Filho and Denadai (2008), the tethered condition tends to overestimate propulsive force when compared to conventional swimming (i.e. non-tethered swimming). It happens because the hand's backward velocity relative to the water is greater in tethered conditions (as the body is not moving) (Martin, Yeater, & White, 1981), which causes higher propulsive force values.

Besides, as a consequence of the zero velocity of fully tethered swimming, all of the mechanical power is spent giving a mass of water a backward velocity change (Pessôa-Filho & Denadai, 2008), i.e. the propulsive efficiency is zero. Differently, in conventional swimming (i.e. non-tethered swimming) part of the total mechanical power is used to overcome drag, while another part is transferred to the water. Thus, as a force increase is detected in tethered conditions, swimmers should be able to apply the proper technique in conventional swimming in order to obtain a greater useful power to the water, that is, an increase of the propelling efficiency (Toussaint et al., 1991).

Thereby, considering the significant changes in swimming velocity, the limits of tethered swimming and hypothetic changes in the coordination and in hand velocity caused by the large and extra-large paddles, coaches have to find a balance between the amount and quality of training directed to technique and power development. Therefore, medium, large and extra-large hand paddles can be a tool with their own limits which should be individualised according to every single swimmer.

Conclusion

It was concluded that medium, large and extra-large paddles significantly influence the force-time curve parameters in tethered swimming and swimming velocity, and that these changes occur accordingly to paddle size. Therefore, it can be suggested that these sizes may be useful for force development in water.

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