Post-activation Potentiation in Propulsive Force after Specific Swimming Strength Training

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Abstract
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We investigated whether a conditioning activity (8×12.5 m with 2.5 min-interval using both hand paddles and parachute) induced post-activation potentiation in swimming propulsive force and whether a swimmer's force level affected a post-activation potentiation response. 8 competitive swimmers (5 males and 3 females, age: 18.4 ± 1.3 years; IPS $= 796 \pm 56$) performed a 10 s maximum tethered swimming test 8 and 4 min before (the highest value was considered as PRE), and 2.5 and 6.5 min after (POST1 and POST2, respectively) the conditioning activity. Rate of force development was not affected, but peak force in POST1 ($p = 0.02$) and impulse in both POST1 ($p = 0.007$) and POST2 ($p = 0.004$) were reduced. Possibly the conditioning activity induced greater fatigue than post-activation potentiation benefits. For instance, the number of repetitions might have been excessive, and rest intervals between the conditioning activity and POST1 and POST2 were possibly too short. There were positive correlations between PRE peak force and changes in peak force and rate of force development. Although conditioning activity was detrimental, positive correlations suggest that weaker swimmers experience a deterioration of performance more than the stronger ones. This conditioning activity is not recommended for swimmers with the current competitive level before a competitive event.

Introduction
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Post-activation potentiation (PAP) is acknowledged as a short-term enhancement in muscle strength and power after performing a high-intensity conditioning activity [35]. It has been demonstrated that such high-intensity exercises during warm-up routines may improve performance in speed and power events [9]. Even though mechanisms responsible for PAP are not entirely known, PAP effects are probably modulated by regulatory myosin light chain phosphorylation, motoneuron excitability, motor units synchronization, and short-term changes in the pennation angle of muscle fibers [17,24,28].

Post-activation potentiation has been documented in different activities and sports such as number of throws in judo [21], 1 000 m rowing ergometer performance [8], and 40- and 100 m running speed [20,34]. In swimming, dry-land exercises induced PAP in peak vertical and horizontal force in the starting block [18], but not IN 15 [18] and 50 m freestyle performance [26]. As it has been demonstrated that conditioning activities should be similar to the desired task

[17], the lack of PAP in the water might be a consequence of the exercise selection for a conditioning activity (pull-ups and jumps), which did not resemble the complexity of swimming motions [23]. Thus, it is conceivable that an in-water strength exercise might serve as a possible more specific trigger for PAP in swimming.

In this sense, hand paddles and parachutes are 2 of the most-used implements to increase specific strength in swimming. Indeed, the artificial enlargement of hands' surface area provided by paddles, and the additional drag created by parachutes, lead swimmers to generate a greater propulsive force in each stroke [3,11,27] without meaningful changes in trajectory, pitch, and sweepback angles of the hand [10,12]. Therefore, it is conceivable that these implements represent a more specific stimulus to induce PAP effects on swimming, and the combined use of both paddles and parachute would increase the need for strength production during swimming compared to the use of either of them alone.

Considering that dry-land exercises failed to show PAP effects on swimming performance, the lack of studies regarding specific stimulus for PAP

in swimming and, finally, that PAP may be an useful approach to acutely increase propulsive force in swimming, the first objective of this study was to investigate if an in-water strength training set performed with hand paddles and parachute would induce PAP in swimming propulsive force. Tethered swimming was used to identify possible acute effects as it represents a valid, sensitive, reliable and widely-used method to assess specific force in swimming [2, 5–7], and also presents good correlation with swimming velocity [1, 19, 22]. Acknowledging that the conditioning activity should be task-specific, trigger PAP benefits, and induce minimal fatigue, we hypothesized that an in-water strength training set would improve swimming propulsive force.

We also assumed that PAP is more likely to be attained in highly-trained athletes [4], because of their greater fatigue resistance [14] and ability to recruit the higher-order motor units that are more sensitive to PAP mechanisms [14, 15]. Secondly, this investigation aimed to verify if possible pre-to-post changes would be related to athletes' propulsive force levels, hypothesizing that swimmers with a higher initial force level would be more likely to experiment PAP effects.

Methods
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Subjects
8 well-trained national competitive swimmers (age: 18.4 ± 1.3 years; IPS = 796 ± 56 points), 5 males (body mass: 73.3 ± 4.6 kg; height: 1.82 ± 0.02 m; fat percentage: 9.3 ± 3.9%) and 3 females (body mass: 60.6 ± 9.2 kg; height: 1.69 ± 0.01 m; fat percentage: 19.3 ± 4.2%), took part in this study. They were front-crawl specialists and experienced with in-water strength training, as informed by their coach. After an explanation about experimental risks and benefits of the research, participants or their responsible signed the written informed consent. All procedures received approval from the university's ethics committee where this study was carried out (Process number: 992/2008). This study complies with all ethical standards put forth by the International Journal of Sports Medicine [16].
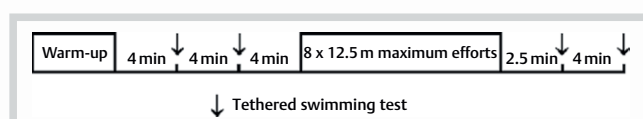
Experimental procedures
The experimental protocol was conducted in the preparatory period of the second macrocycle of the year, in which training frequency varied from 6 to 9 sessions per week and mean weekly volume (considering the whole season) reached 39 456 ± 9 360 m. During the testing week, athletes swam 28 500 m in a total of 6 training sessions. After the warm-up (1 000 m of low-to-moderate intensity swimming = 400 m of free swimming + 200 m kick + 200 m drills + 200 m of free swimming), swimmers performed a tethered swimming test (which will be described later) twice before (PRE1 e PRE2) and twice after (POST1 and POST2) a conditioning activity (○ **Fig. 1**). POST1 and POST2 were performed 2.5 and 6.5 min after the conditioning activity, respectively. PRE1 and PRE2 tests were used to investigate whether the

test itself could induce PAP and were separated by 4 min. Four minutes after PRE2, swimmers performed the conditioning activity, which consisted of 8 maximum efforts of 12.5 m starting every 2.5 min using both hand paddles (245 cm^2) and parachute (400 cm^2). POST1 and POST2 were used to assess possible PAP over time. Hand paddles surface area was assessed by computerized planimetry using the ImageJ software (v. 1.43, National Institute of Health, Bethesda, USA). Parachute area was obtained by multiplying the length of its sides (i.e., 20 cm × 20 cm). During the in-water strength training set, the hand paddles were fixed to the swimmer's hands by 2 adjustable straps, positioned close to the wrist and middle finger, whereas the parachute was tethered to a belt around the waist of each swimmer and kept approximately 1 m away from the swimmer's feet. All testing procedures were carried out during one session, between 2:00 and 4:00 PM, in an indoor pool (water temperature: 27 °C) using front-crawl full technique (i.e., arm stroke and leg kick). Propulsive force was evaluated by means of a fully-tethered swimming system (CEFISE, Nova Odessa, Brazil) composed by a load cell with 4 strain gages and 2 000 N of maximum capacity. One of its extremities was attached to a special designed support fixed to the starting block while the other was connected to an inextensible cable system, in which the swimmer was tethered on the waist through an adjustable belt. Deformations in the load cell generated by swimmer's efforts during testing procedures were recognized by an A/D interface and stored at 200 Hz.

The test consisted of a 10-s maximal swimming effort with self-selected stroke rate. The beginning (after approximately 5 s of moderate swimming) and the end of the test protocol were signaled by a whistle. To avoid inertial effects, 1 s was given between the whistle and the start of data acquisition, as adopted in previous investigations [3, 22]. Swimmers were requested to hold their breath to avoid major modifications of stroke kinematics [11]. Athletes were familiar with the test since it had been performed during their training sessions with the aim of monitoring training responses.

Individual force-time curves were smoothed using a fourth-order Butterworth low-pass digital filter with a cut-off frequency of 8 Hz, defined through residual analysis [33]. Then, main points shown in ○ **Fig. 2** were marked in 8 consecutive

Fig. 1 Timeline of experimental procedures with rest interval between warm-up, tests and conditioning activity.
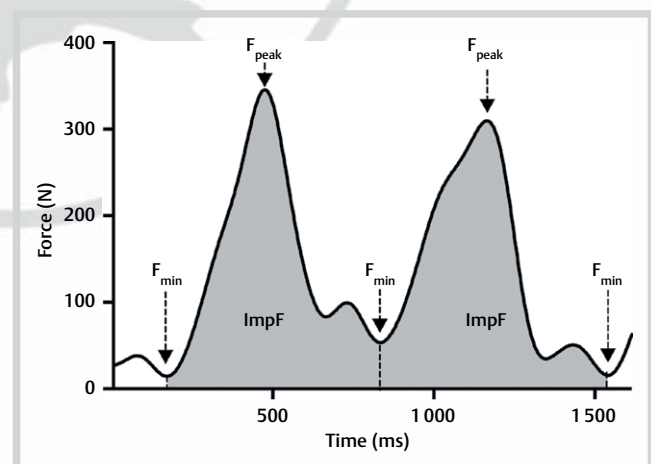
Fig. 2 Example of 2 consecutive cycles of a front-crawl curve and also the main points used for force-time curve analysis. F_{peak} = peak force; ImpF = Impulse; F_{min} = minimum force.
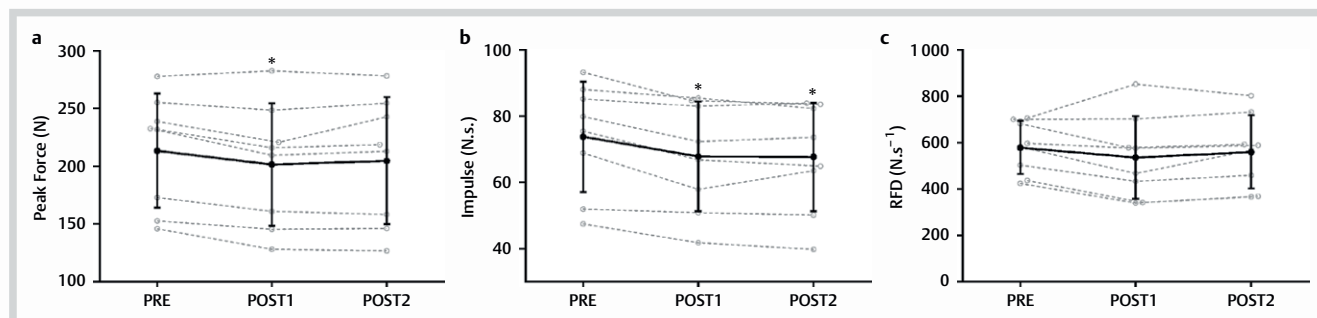
Fig. 3 Descriptive statistics (M±S) of Peak force (N, Panel **a**), Impulse (N·s, Panel **b**) and Rate of force development (RFD, N·s-1, Panel **c**) * p<0.05 compared to PRE. Dashed lines represent individual values and continuous line represents mean.

Table 1 Correlations between percent changes (Δ%) and PRE values.

	Δ% Peak Force		Δ% Impulse		Δ% RFD	
	r	*P*-value	r	*P*-value	r	*P*-value
Peak Force	0.71	0.04	0.10	0.80	0.79	0.02
Impulse	0.76	0.03	0.20	0.63	0.76	0.03
RFD	0.58	0.13	0.07	0.86	0.70	0.06

complete cycles (i.e., the interval between 2 successive lowest points) for the assessment of:

1. Peak force (expressed in N): the highest force value between 2 consecutive minimum force values (ICC=0.95, CI 95%=0.77–0.99, p<0.0001; CV=3.7%, CI 95%=0.9–6.6%);
2. Impulse (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=0.99, CI 95%=0.93–1.00, p<0.0001; CV=2.2%, CI 95%=0.9–3.6%);
3. Rate of force development (RFD, expressed in $N·s^{-1}$): ratio between force variation (ΔF=peak force minus its previous minimum force value) and the 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=0.83, CI 95%=0.37–0.96, p=0.003; CV=8.0%, IC 95%=3.5–12.5%).

Statistical analysis

The assumptions of normally distributed samples and sphericity were verified using Shapiro-Wilk and Mauchly tests, respectively. A paired t-test was used to compare PRE1 with PRE2 values. Once there was no difference between these tests, the highest value represented PRE and was used for further analysis. Repeated measures ANOVA computed possible acute effects of the described training set by comparing PRE, POST1 and POST2. If sphericity was violated the p-values were adjusted by the epsilon Greenhouse-Geisser correction factor. Multiple pairwise comparisons were made by Bonferroni test. Moreover, ANOVA's effect size was computed through the partial eta squared (η^2) while post-hoc comparisons' effect sizes (ES) were calculated through Cohen's *d*. All data are expressed as means±standard deviations (M±S). PRE-to-POST1 and PRE-to-POST2 percent changes (Δ%) of all force-time curve parameters were calculated and the highest value was retained for further analysis. Pearson product-moment correlation coefficients were used to analyze the relationship between percent changes and PRE values. For all situations the significance level was set at p<0.05. Analyses were conducted using SPSS for Windows (Version 17.0; SPSS, Inc., Chicago, IL, USA).

Results

The in-water strength training set negatively affected peak force (○ **Fig. 3a**, $F_{2,14}$=7.93, p=0.005, η^2=0.53) and impulse (○ **Fig. 3b**, $F_{2,14}$=18.10, p<0.0001, η^2=0.72), but had no effect on RFD (○ **Fig. 3c**, $F_{2,14}$=1.69, p=0.23, η^2=0.20). Indeed, pairwise comparison revealed a lower peak force in POST1 (p=0.02, ES=0.23), and also impulse in both POST1 (p=0.007, ES=0.36) and POST2 (p=0.004, ES=0.37) compared to PRE. There was no difference between POST1 and POST2.

○ **Table 1** displays all the correlation coefficients among force-time curve parameters in PRE and pre-to-post percent changes.

Discussion

The first aim of this study was to investigate whether an in-water strength training set performed with hand paddles and parachute would induce PAP in tethered swimming force. Post-activation potentiation, which is also known as an activity-dependent potentiation, refers to an enhanced muscle contractile response (i.e., increased strength production) induced by a prior conditioning activity. The main suggested mechanisms responsible for PAP are phosphorylation of myosin regulatory light chains, increased recruitment of higher order motor units, and short-term changes in the pennation angle of muscle fibers. Regulatory light chain phosphorylation increases the sensitivity of the actin-myosin interaction to Ca^{2+}, and alters the structure of the myosin head, resulting in a higher force-producing state of cross-bridges. Regarding the second mechanism, previous contractions elevate the excitation potential across synaptic junctions at the spinal cord and, as a result, postsynaptic potentials increase as well as the recruitment of higher order motor units increase during subsequent activity, enhancing force production and rate of force development. Pennation angle of muscle fibers influences force and power production, as the force produced by the muscle and applied to the tendon is corrected by angle cosine. Consequently, a smaller pennation angle provides a mechanical advantage to force transmission to the tendon. In addition, PAP has already been observed in animal, ex-vivo and human models, following both electrical and voluntary stimulation, and in different movements and sports. Then, in theory, any type of conditioning activity could enhance contractile response during swimming.

However, previous muscle contraction produces both fatigue and PAP, and the net result of these 2 events determines whether

the performance in a subsequent task is positively, negatively, or not affected. Muscle contractile ability, post stimulus, depends on the time courses of fatigue recovery and PAP decline rate. Thus, a positive balance of the coexistence of PAP and fatigue results in a potentiated muscle contractile ability [25]. According to Tillin & Bishop [28], fatigue plays a negative effect on PAP and "…seems more dominant in the early stages of recovery and, consequently, performance of subsequent voluntary activity is diminished or unchanged" (p. 156). Consequently, PAP is more likely to be achieved in highly-trained athletes due to their greater fatigue resistance resulting from intense training regimes [14], as well as their ability to recruit higher-order motor units more sensitive to PAP mechanisms [14,15]. Nevertheless, our results demonstrated that the in-water training set used herein did not enhance force production capacity neither rate of force development up to 6.5 min. In fact, the conditioning activity was consistently detrimental for impulse and peak force, which decreased for 8 and 7 participants, respectively, suggesting an important role played by fatigue.

The lack of PAP's beneficial effects may be attributed to certain characteristics of the conditioning activity (i.e., high number of repetitions, short rest interval) which INDUCED a greater fatigue, consequently, AND MASKED the effects of PAP. It is possible, though, that another training set that provides the appropriate balance between neuromuscular activation and fatigue could be beneficial for those who experienced detrimental effects and lower in-water peak force and RFD levels.

Practically, the optimal balance between fatigue and neuromuscular activation could come from twofold: a) the reduction of the muscle mechanical work and/or b) a greater rest interval between the conditioning activity and subsequent exercise. Concerning the first, it is obvious that a higher training volume induces greater fatigue, especially in high-intensity resisted exercises as seen in the current in-water strength training set. Considering that there is no current consensus regarding the proper volume for reaching PAP, both in dry-land activities [13] and in aquatic sports, as well as no recommendation regarding conditioning activity for swimming, we chose to use a traditional in-water training set for such purpose.

Secondly, it is well accepted that rest interval noticeably affects PAP magnitude [13]. A recent meta-analysis reported that when rest intervals after the conditioning activity range from 8 to 12 min, moderate improvements on vertical jump performance are observed, whereas only small changes can be noticed for rest intervals from 4 to 7 min and more than 16 min [13]. Unfortunately, due to organizational and schedule limitations of the club, we were not able to continue testing swimmers greater than 6.5 min. Therefore, studies concerning rest intervals during in-water strength training sets are warranted.

Additionally, the present study also aimed to verify if possible pre-to-post changes would be related to swimmer's propulsive force levels. Even though most subjects decreased force-time curve parameters after the conditioning activity, we found positive correlations between both peak force and impulse, and the PRE-POST percent changes for peak force (r = 0.71 and 0.76, respectively) and RFD (r = 0.79 and 0.76, respectively). This indicates that swimmers with lower peak force and impulse were also those with the greater reduction in tethered swimming performance. Due to a same absolute resistance (same size of paddles and parachute), a higher relative intensity in swimmers with lower initial force levels may have resulted in greater

fatigue. This emphasizes the importance of the individualization of the training set for possible PAP effects.

Interestingly, one subject increased peak force and RFD in POST1 while another experienced positive effects in RFD in POST2. Both increases were from swimmers with the highest peak force and RFD values in PRE. This indicates that the current training set were, in fact, effective for some athletes with a greater ability to mobilize their neuromuscular system during swimming. Because of this, it can be suggested that the intensity of muscle contractions induced by paddles and parachute herein was sufficient to induce PAP, although, in this case, the rest interval should be increased. In accordance, Turner et al. [31] also observed PAP effects on 10 and 20 m running sprint performance after a plyometric set of jumps with only 10 % of body weight. Additionally, Tobin & Delahunt [29] noticed improvements in jump height and peak force after a plyometric set.

Finally, it is important to note that possible positive effects in tethered swimming do not necessarily generate greater swimming velocity. Although this is a valid, sensitive and reliable method [2,5–7], its correlation with swimming performance may range from 0.81 to 0.92 [22], indicating that other factors such as technique [30] and aerobic capacity [32] also play an important role for the final competitive outcome.

Practical Application
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The findings presented here indicate that the current hand paddles and parachute-based conditioning activity should not be used before main competitive events, at least for swimmers with the present competitive and/or propulsive force levels.

Conflict of interest: The authors have no conflict of interest to declare.

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