

# Post-activation performance enhancement (PAPE) after a single bout of high-intensity flywheel resistance training

**AUTHORS:** Sergio Maroto-Izquierdo<sup>1,2</sup>, Iker J Bautista<sup>3</sup>, Fernando Martín Rivera<sup>4</sup>

<sup>1</sup> Department of Health Sciences, European University Miguel de Cervantes, Valladolid, Spain

<sup>2</sup> Proporción A, Applied Sports Science Center, Valladolid, Spain

<sup>3</sup> Department of Physiotherapy, Catholic University of Valencia, Valencia, Spain

<sup>4</sup> Research Group in Prevention and Health in Exercise and Sport, University of Valencia, Valencia, Spain

**ABSTRACT:** This study investigated the post-activation performance enhancements (PAPE) induced by a high-intensity single set of accentuated eccentric isoinertial resistance exercise on vertical jump performance. Twenty physically active male university students performed, in randomized counterbalanced order, two different conditioning activities (CA) after a general preestablished warm-up: a conditioning set of 6 maximum repetitions at high intensity (i.e., individualized optimal moment of inertia [ $0.083 \pm 0.03 \text{ kg}\cdot\text{m}^2$ ]) of the flywheel half-squat exercise in the experimental condition, or a set of 6 maximal countermovement jumps (CMJ) instead of the flywheel exercise in the control condition. CMJ height, CMJ concentric peak power and CMJ concentric peak velocity were assessed at baseline (i.e., 3 minutes after the warm-up) and 4, 8, 12, 16 and 20 minutes after the CA in both experimental and control protocols. Only after the experimental protocol were significant gains in vertical jump performance ( $p < 0.05$ , ES range 0.10–1.34) at 4, 8, 12, 16 and 20 minutes after the CA observed. In fact, the experimental protocol showed greater ( $p < 0.05$ ) CMJ height, concentric peak power and concentric peak velocity enhancements compared to the control condition. In conclusion, a single set of high-intensity flywheel training led to PAPE in CMJ performance after 4, 8, 12, 16 and 20 minutes in physically active young men.

**CITATION:** Maroto-Izquierdo S, Bautista IJ, Martín-Rivera F. Post-activation performance enhancement (PAPE) after a single bout of high-intensity flywheel resistance training. *Biol Sport*. 2020;37(4):343–350.

Received: 2020-05-06; Reviewed: 2020-05-27; Re-submitted: 2020-06-01; Accepted: 2020-06-06; Published: 2020-07-05.

Corresponding author:

**Fernando Martín**

Faculty of Physical Activity and Sports Science

University of Valencia

Blasco Ibáñez avenue, 13

46010 Valencia, Spain

Phone: +34 963 864 339

Fax: +34 963 864 353

E-mail: fernando.martin-rivera@

uv.es

## Key words:

Isoinertial  
Eccentric overload  
Vertical jump  
Warm-up  
Muscle power

## INTRODUCTION

Throughout the scientific literature, numerous physical and physiological strategies have been proposed to increase neuromuscular performance in both chronic and acute ways. Chronic neuromuscular enhancements are traditionally related to different muscular strengthening methodologies and periodization approaches [1]. With respect to acute performance enhancements, much attention has been given to the possibility that performance optimization may be achieved through warm-up strategies. The employment of brief (i.e., low volume) and high- or moderate-intensity conditioning activities (CA) stands out among these preparatory strategies, leading to significant neuromuscular improvements in the working muscles [2].

Accordingly, these performance enhancements have been observed immediately after (< 3 minutes) the application of an intense voluntary muscular contraction when peak force and rate of force development enhancements were assessed by an electrically evoked twitch contraction [2]. This phenomenon is called post-activation potentiation (PAP). However, when a significant rest period is applied after a high-intensity exercise-based warm-up with the intent of

enhancing subsequent voluntary, rather than electrically evoked, force production (peaking at 7–10 minutes after the strengthening activity), the post-activation performance enhancement (PAPE) phenomenon occurs [3]. In addition, whereas PAP underpinning mechanisms are related to myosin regulatory light chain phosphorylation, PAPE may potentially be associated with increases in muscle temperature, muscle water content and muscle activation level, although its underpinning mechanisms are yet to be defined [2]. However, different PAPE protocols have shown significant neural (e.g., force production, EMG amplitude) and functional effects (e.g., jump or throw performance, sprint and some sport-specific tasks) [4].

PAPE is widely studied after single sets of heavy-load (i.e., 80–90% 1-RM) resistance exercises employing free-weight [5] and variable resistance training [6]. Indeed, it seems that high-intensity exercise is required to achieve greater acute performance enhancements [7]. In addition, it has been shown that multiple sets of strengthening activities induced a considerably larger PAPE effect than a single set, particularly in beginners and weaker participants [4, 7]. However, independently of training intensity and volume,

during traditional concentric-eccentric resistance exercise performed at maximal concentric velocity, the eccentric phase is clearly underloaded due to the well-described force-velocity characteristics of muscles. Hence, eccentric-overload (EO) resistance training emerges as an alternative method to prescribe effectively intensity, relative to the force generation capabilities of the eccentric muscle action, and to avoid the negative work isolation (i.e., favouring the stretch-shortening cycle use, while creating minimal interruption in the natural mechanics of the selected exercise and movement) [8, 9]. In fact, several studies have demonstrated that the inclusion of an accentuated eccentric loading may generate higher subsequent post-activation explosive performance enhancement in lower [10, 11] and upper limbs [12, 13], especially when plyometric CA rather than traditional high- or moderate-intensity weight exercises were used. However, eccentrically reinforced training with gravitational resistances is not widely used due to substantial mechanical difficulties and little practical application encountered with this method.

Among different technologies allowing for EO, flywheel training is one of the most utilized exercise paradigms with established efficacy in different scenarios [14]. Flywheel technology bases its operation on the energy produced in the system during a maximum concentric action, which is stored and maintained during the subsequent eccentric action due to its inertial characteristics, providing a reinforced lengthening action when a short and concentrated braking action occurs at the end of the eccentric phase [15]. By means of this approach, EO is generated in the system, and greater amounts of overload are achieved with higher inertial loads [16], which is an advantage by allowing us to use the stretch-shortening cycle while providing an optimal load for each phase of the movement in a mechanically simple way.

Recently, several studies have demonstrated the effectiveness of flywheel devices to provide significant acute effects on explosive performance (although all of them have referred to these effects as “PAP”) in athletes [17–19] and healthy subjects [20, 21]. Beato *et al.* [19, 21] and Timon *et al.* [20] have found significant vertical jump (countermovement and squat jump, respectively) enhancements after 3 to 9 minutes of rest subsequent to a flywheel squat PAPE protocol. These studies employed high-volume (i.e., 3 sets of 6 repetitions) and low-intensity (i.e., moment of inertia of 0.03–0.06 kg·m<sup>2</sup>) PAPE designs [19–22]. This seems to indicate that regardless of individual characteristics a high-volume EO-based warm-up positively influences the PAPE response. Nonetheless, Cuenca-Fernandez *et al.* [18, 23] observed similar PAPE effects (i.e., vertical force production and velocity) in the swimming start performance at 8 minutes after only 4 reps of a swimming-specific flywheel exercise at low intensity (0.05 kg·m<sup>2</sup>). Although these findings are supported by previous studies in which it was shown that athletes or stronger individuals express greater potentiation levels after a single-set CA [4], the interaction between volume and intensity plays an undisputed role when examining PAPE responses, particularly regarding EO CA [22]. Notwithstanding, to the best of our knowledge, no studies

have analysed PAPE time course responses after high-intensity and low-volume iso-inertial EO CA.

Given the current options to produce EO during warm-up CA and the hypothesis that a unique set of high-intensity EO induced by an iso-inertial flywheel stimulus implementing an appropriate warm-up may be enough to promote PAPE, we designed a study to investigate the time course acute effects on vertical jump performance at 4, 8, 12, 16 and 20 minutes following a single-set of high-intensity EO exercise induced by a flywheel device in physically active men.

## MATERIALS AND METHODS

### *Experimental Approach to the Problem*

A randomized single-blind crossover study design was performed to investigate the post-activation performance enhancement (PAPE) time course (4, 8, 12, 16 and 20 minutes) after a single bout of high-intensity flywheel resistance exercise. Participants came to the laboratory for three consecutive weeks, performing 6 sessions (Figure 1). During the first week, three familiarization sessions, separated by 48 hours, were completed to enlighten participants with the study procedures (i.e., CMJ test, flywheel operation and PAPE protocol). In the second week, a session was performed to establish the optimal inertial load that maximized exercise power. In the third week, participants underwent two randomized and counterbalanced testing sessions separated by 72 hours. Each testing session was preceded by a comprehensive task-specific warm-up designed to have an effect on the musculature most closely related to the jump performance. Three minutes after the warm-up, a baseline countermovement jump (CMJ) was recorded, and participants performed either the experimental or control conditioning activity. The experimental protocol consisted of a conditioning set of 6 maximum repetitions at high intensity (i.e., using the optimal load that maximizes concentric peak power output determined in session 4) of the flywheel half-squat exercise, while the control protocol involved a set of 6 maximal CMJs instead of the flywheel exercise. Vertical jump height, concentric peak power output, and maximal concentric velocity were collected during each CMJ at baseline, and 4, 8, 12, 16 and 20 minutes after the conditioning activity.

### *Subjects*

Twenty healthy sports science undergraduate male students volunteered for the study ( $23.4 \pm 2.9$  years,  $174.0 \pm 9.2$  cm,  $69.4 \pm 15.4$  kg, and  $16.5 \pm 6.4\%$  fat mass). All of them had, at least, one year of experience with flywheel training, and no history of neurological disorders or lower limb orthopaedic injuries. None of them were taking drugs, medications or other substances that could alter their performance during testing. Moreover, participants recorded and then maintained their sleeping, eating and drinking habits in the 48 hours prior to each testing session. Stimulant consumption was recorded on the day of the first familiarization session and replicated on the next familiarization and testing session. Participants were informed of the purposes and risks involved in the study before

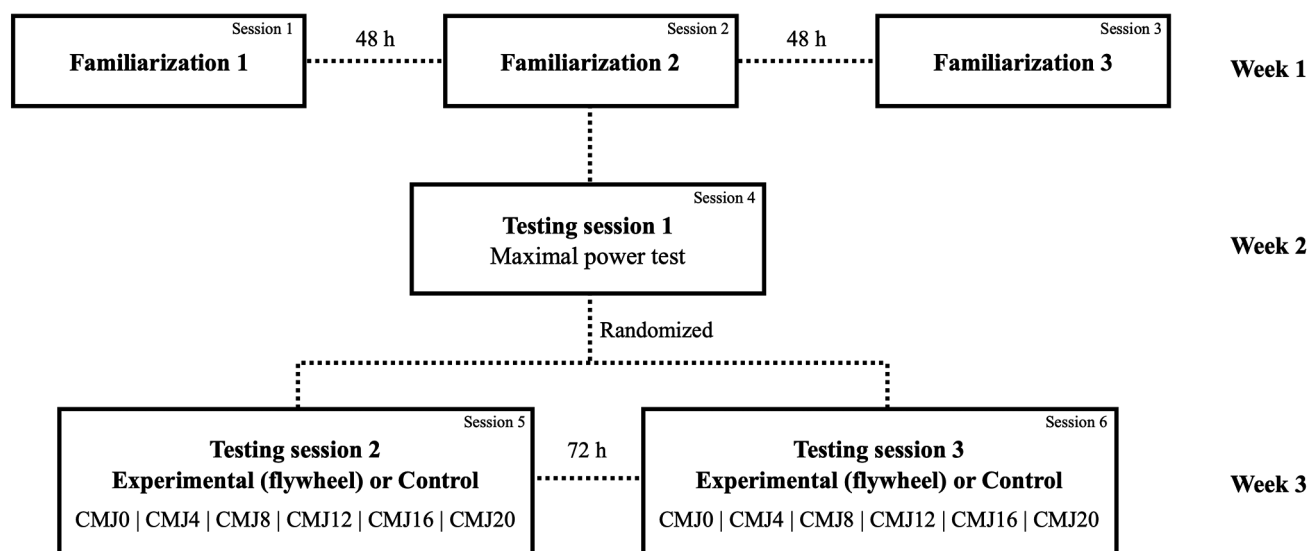


FIG. 1. Experimental design scheme.

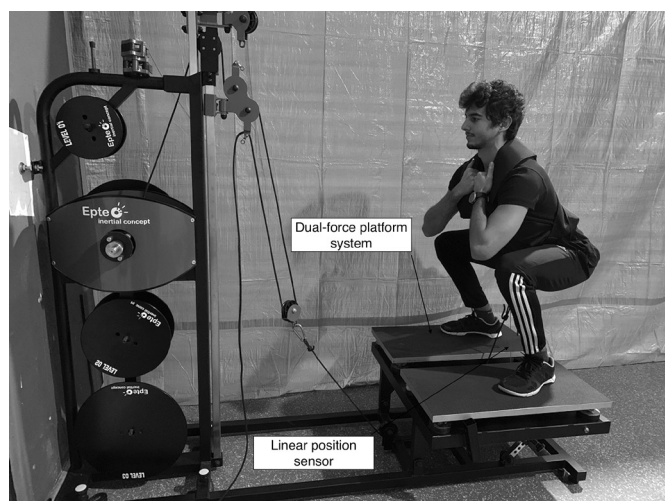


FIG. 2. Flywheel device used to induce PAPE.

giving their informed written consent to participate. The study procedures were in accordance with the principles of the Declaration of Helsinki and were approved by the local Institutional Review Board (H1421157445503).

### Procedures

Participants came to the laboratory for three consecutive weeks, performing 6 sessions (Figure 1). During the first week, three familiarization sessions, separated by 48 hours, were completed to enlighten participants with the study procedures (i.e., CMJ test, flywheel operation and PAPE protocol). In the second week, a session was performed to establish the optimal inertial load that maximized exercise concentric peak power. In accordance with the protocol proposed by De Hoyo et al. [17], each participant performed an inertial incremental test to determine the optimal load in which the highest

concentric peak power was developed in the squat exercise on a flywheel device (EPTE Inertial Concept, L'Alcudia, Spain) (Figure 2). Participants performed 4 repetitions of the exercise with different progressive loads. The first repetition was executed to start the movement and to accelerate the flywheel system. Then, during the next three repetitions, participants were asked to push with maximal effort (i.e., maximum possible concentric speed) through the entire concentric action, which ranged from a 90° knee flexion to near full extension. At the end of this concentric action, the flywheel strap wound back due to inertial forces, which initiated the reversed eccentric action. During the first third of the eccentric action, participants were instructed to resist gently, and thereafter to apply maximal braking force to stop the movement at about a 90° knee flexion [15]. To ensure that participants employed the same squat depth at each repetition, an adjustable tripod with a telemetric photocell (Microgate, Bolzano, Italy) was placed at the side of the flywheel. The telemetry photocell emitted a sound when the knees reached the individual set height. The flywheel was equipped with 6 combinable inertial wheels: 2x0.0095 kg·m<sup>2</sup>, 2x0.0472 kg·m<sup>2</sup>, 2x0.151 kg·m<sup>2</sup>. The load was progressively increased (a 3-minute rest period was applied between sets) according to the periodization series shown in Table 1. Only the highest concentric peak power repetition was collected for further analysis. The optimal load was determined when concentric peak power decreased in comparison with the previous load. The optimal moment of inertia that maximized concentric peak power was 0.083 (± 0.03) kg·m<sup>2</sup>. Data were collected with a dual-force platform system (2,000 Hz sampling rate, ForceDeck FD4000, Vald Performance, Australia) and a linear position sensor (1,000 Hz sampling rate, T-Force, Ergotest, Murcia, Spain).

In the third week, participants were assigned in a randomized and counterbalanced order to two different testing conditions sepa-

rated by 72 hours. Each testing session was preceded by a comprehensive task-specific warm-up designed to have an effect on the musculature most closely related to the jump performance. It consisted of 5 minutes of cycling followed by 5 minutes of a dynamic stretching protocol (i.e., forward leg swings, ankle dorsi- and plantarflexion, side leg swings, high knees, heel flicks, squats and lunges) [18]. Each exercise was performed for 20 seconds, and the entire set was repeated twice [18]. Then, two sets of five continuous unloaded squats (i.e., non-jumping) interspersed by 30 seconds at a rhythm of 2/2 (eccentric/concentric) tempo and 1/1 tempo, respectively, were performed [6]. After 1-minute rest, five continuous CMJs were performed at ~70% of the participants' perceived maximum and, after a further 30 seconds rest, 6 maximal CMJs were performed [6]. Three minutes after the completion of the warm-up, a maximal pre-intervention CMJ trial was performed to establish baseline (i.e., after warm-up) performance. A conditioning set of 6 maximum repetitions at high intensity (i.e., using the optimal load that maximizes concentric peak power output determined beforehand, with the same aforementioned technical requirements) of the flywheel squat exercise under the experimental condition, or a set of 6 maximal CMJs instead of the flywheel exercise in the control condition, was then performed before the participants completed a CMJ 4 minutes, 8 minutes, 12 minutes, 16 minutes and 20 minutes later with participants receiving verbal encouragement to jump as high as possible. The post-intervention intervals were selected from previous data describing the time course of the performance augmentation (PAPE) response [22]. During the withdrawal period between each trial participants were not allowed to perform any physical activity or exercise. The dual force platform system described above was used to assess vertical jump performance during a self-selected depth CMJ with hands on hips [24].

Vertical jump height, concentric peak power output, and maximal concentric velocity were collected during each CMJ at baseline,

4, 8, 12, 16 and 20 minutes after the warm-up. All testing sessions were controlled by the same three researchers. An independent researcher monitored the entire warm-up protocol to ensure that the exercises were performed properly and at the accurate time. The investigator in charge of collecting vertical jump performance at 4, 8, 12, 16 and 20 minutes after the warm-up was unaware of whether participants had previously performed either the experimental or control protocol (i.e., single-blind condition). All experimental sessions took place under similar environmental conditions (~23°C; ~60% humidity) and at the same time of day. In addition, this experimental study has been designed according to Blazevich & Babault's [2] study design considerations. Table 2 shows the standardization items taken into account in the present experimental design and intervention.

### Statistical Analysis

All variables were expressed as a mean and standard deviation and were analysed using a statistical package (SPSS Inc., Chicago, Illinois, USA). The normality assumption by Shapiro-Wilks was identified for each variable. For reliability measures, absolute (i.e., standard error measurement [SEM]) and partial reliability (intraclass correlation coefficient model 2.1 [ICC<sub>2,1</sub>]) were calculated for baseline conditions. A repeated measures analysis of variance (RM ANOVA [2 x 6]) was performed to assess the influence of the "condition" (i.e., control condition vs. experimental condition) and "time moment" variable (i.e., baseline and after 4 min, 8 min, 12 min, 16 min and 20 min) over jump height, power and velocity in the CMJ test. In the event that the sphericity assumption was not met, degrees of freedom were corrected using Greenhouse-Geisser estimation. Post hoc analysis was corrected using Bonferroni adjustment. Hedges' G and the associated confidence intervals (CI) were used to assess the magnitude of mean differences between control and experimental conditions. Significant differences were established at  $p < 0.05$ .

**TABLE 1.** Compliance with Blazevich & Babault's(5) study design considerations for PAPE studies.

Comprehensive list	Y/N
Comparison between at least two conditions.	Y
Familiarization of the performance task or test to avoid learning effects.	Y
Randomization between conditions on separate days.	Y
Single blinding (researcher).	Y
Control for muscle temperature	N
Time of day.	Y
Hydration.	Y
Physical activity performed in the days prior to testing.	Y
Potential use of ergogenic aids.	Y

Abbreviations: Y: Yes; N: No.

**TABLE 2.** Inertial load progression followed during the maximal muscular power incremental test.

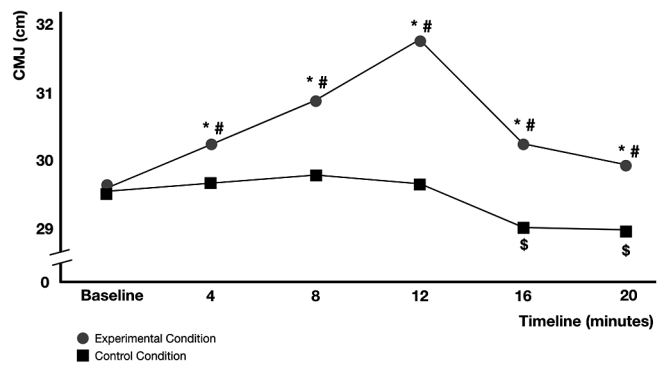
Load progression	Inertial load (kg·m <sup>2</sup> )
1S	0.0095
2S	0.0190
1M	0.0472
1M + 1S	0.0567
1M + 2S	0.0662
2M	0.0945
2M + 1S	0.1040
2M + 2S	0.1135

Abbreviations: S, small; and M, medium inertial wheels.

**RESULTS**

In the experimental condition, absolute (i.e., SEM) and partial reliability (i.e., ICC) for the jump height variable were 0.55 cm and 0.99 (95% CI 0.98–0.99). Meanwhile, for the control condition absolute and partial reliability were 0.50 cm and 0.99 (95% CI 0.98–0.99), respectively. The sphericity assumption was not met for the “condition x time moment” ( $\chi^2_{(9)} = 76.0, p < 0.01$ ) interaction. Therefore, degrees of freedom were corrected using Greenhouse-Geisser estimation ( $\epsilon = 0.35$ ). RM ANOVA revealed statistically significant differences for the main effect of “condition” ( $F_{[1, 19]} = 109.1; p < 0.001$ ) and “condition x time moment” interaction ( $F_{[1.47, 27.9]} = 17.6; p < 0.001$ ); see Figure 3 and Table 3.

In relation to power (W) and velocity (m/s) variables, ANOVA RM showed statistical differences in “condition” ( $F_{[1, 19]} = 82.2; p < 0.001$ ; and  $F_{[1, 19]} = 261.9; p < 0.001$ , respectively) and the “condition x time moment” interaction ( $F_{[1.66, 31.50]} = 20.5; p < 0.001$  and  $F_{[5, 95]} = 30.9; p < 0.001$ , respectively). Mean differences, 95% CI, significance and effect size are displayed in Table 3.



**FIG. 3.** Vertical jump performance (height, cm) at baseline, 4, 8, 12, 16 and 20 minutes after the CA for both experimental (flywheel) and control condition. \* Significantly different from baseline value under PAPE condition, where  $* P < 0.001$ . \$ Significantly different from baseline value under control condition, where  $\$ P < 0.001$ . # Significantly different from control condition value, where  $\# P < 0.001$ .

**TABLE 3.** Mean difference (MD), confidence intervals (CI) of 95%, significance and effect size with CI of differences between experimental (PAPE) vs. control condition in jump height (cm), peak concentric velocity (m/s) and concentric peak power (W) at each time tested (Baseline, post 8, 12, 16 and 20 minutes).

Variable	Baseline	Post 4 minutes	Post 8 minutes	Post 12 minutes	Post 16 minutes	Post 20 minutes
<b>Jump Height (cm)</b>						
<b>MD</b>	0.04	0.58	1.12	2.12	1.22	0.93
<b>CI 95%</b>	-0.04–0.13	0.29–0.86	0.55–1.66	1.57–2.66	0.90–1.53	0.71–1.16
<b>P-value (sig)</b>	0.298	< 0.001 *	< 0.001 *	< 0.001 *	< 0.001 *	< 0.001 *
<b>Effect Size</b>	0 (-0.19–0.20)	0.07 (0.21–0.07)	0.13 (0.27–0)	0.25 (0.40–0.10)	0.16 (0.30–0.02)	0.11 (0.21–0.02)
<b>Velocity (m/s)</b>						
<b>MD</b>	0.002	0.053	0.10	0.35	0.27	0.23
<b>CI 95%</b>	-0.005–0.01	0.026–0.080	0.05–0.16	0.25–0.44	0.30–0.23	0.19–0.27
<b>P-value (sig)</b>	0.489	< 0.001*	< 0.001 *	< 0.001 *	< 0.001 *	< 0.001 *
<b>Effect Size</b>	0.04 (0.18– -0.10)	0.22 (0.38–0.06)	0.46 (0.67–0.25)	1.34 (1.82–0.87)	1.18 (1.60–0.75)	0.96 (1.32–0.60)
<b>Power (W)</b>						
<b>MD</b>	1.35	17.63	33.75	63.83	36.19	27.96
<b>CI 95%</b>	-1.13–3.83	9.04–26.22	17.17–50.33	47.43–80.25	26.85–45.53	21.39–34.53
<b>P-value (sig)</b>	0.269	< 0.001 *	< 0.001 *	< 0.001 *	< 0.001 *	< 0.001 *
<b>Effect Size</b>	0 (0.20– -0.19)	0.06 (0.20– -0.09)	0.10 (0.31– -0.10)	0.19 (0.35–0.04)	0.12 (0.27– -0.03)	0.09 (0.23– -0.05)

\* significant differences between experimental vs. control condition, in which  $*P < 0.001$ . \$ MD (mean differences) between experimental vs. control condition

## DISCUSSION

The aim of this study was to determine the acute effects of time course on vertical jump performance after a high-intensity (in terms of optimum muscle power output regarding moment of inertia) and low-volume CA induced by a flywheel device in physically active men. Post-activation performance enhancement (PAPE) was observed only after the warm-up which included the flywheel CA. Participants under experimental condition (i.e., flywheel protocol) showed significant ( $p < 0.05$ ) increases in vertical jump height, concentric peak power and concentric peak velocity in a CMJ at 4, 8, 12, 16 and 20 minutes after the CA compared to baseline data. In addition, significant differences were found between control and experimental protocols at each time tested (after 4, 8, 12, 16 and 20 minutes). Hence, it seems that a single bout of high-intensity accentuated eccentric isoinertial resistance exercise is adequate to have a significant impact on post-activation explosive performance enhancement.

However, the underpinning mechanisms of these findings have not been broadly elucidated yet. Blazeovich & Babault [2] have lately proposed that, while myosin regulatory light chain phosphorylation at low levels of calcium is the most likely phenomenon underpinning PAP, high-intensity strength training (i.e., PAPE protocol exercises) requires maximal or near-maximal levels of muscle activation, and thus PAP cannot directly influence them. Furthermore, twitch contractile enhancements have been shown without any observable PAPE (e.g., vertical jump height) [25]. Consequently, PAPE is a different phenomenon which occurs as of 4 minutes after CA, likely influenced by other physiological changes, such as increases in muscle temperature, muscle activation and/or coordination (learning or motivational effects), or improvements in muscle function through non-related myosin regulatory light chain phosphorylation mechanisms, such as intracellular water accumulation [2]. Moreover, the lack of PAPE when PAP occurs may be affected not only by fatigue (as occurs with PAP when, for example, high volume doses of strength exercises are prescribed), but also by a motor pattern interference effect (i.e., “perseveration”), which suggest a perceived loss of coordination in a sequentially performed task [2].

Traditionally, these PAPE phenomena have been induced by exercises based on the individual concentric maximum strength (i.e., lifting and lowering weights at a certain percentage of 1-RM) [4]. However, given the current options to promote PAPE, the type of CA seems to be a determining factor. It has been shown that plyometric activities [10, 12] and exercises with accentuated eccentric load [11], in which a greater relative and more optimal load is provided during the eccentric phase, may induce greater acute effects on subsequent explosive performance. This is probably due to an optimized use of the stretch-shortening cycle, with a preferential recruitment of type II motor units, less central and peripheral fatigue, and greater discharge rates with higher force production during the eccentric phase [15, 26]. Therefore, the employment of CA which involve the use of the stretch-shortening cycle concurrent with an optimal load

in both concentric and eccentric muscle contractions (e.g., flywheel training) may allow a greater potentiation effect to be achieved. This would explain the absence of an enhancing effect in the control condition, since, unlike a series of simple CMJs, the flywheel stimulus operation is similar to variable resistance training (i.e., elastic bands implementation during free-weight exercises) [14]. Mina and colleagues [6] established that variable resistance training provides a more rapid muscle stretch resulting from force potentiation, greater elastic energy storage in the muscle, an increased time of muscle activation, or changes in relative contributions of muscle and tendon allowing the muscle to operate at lower shortening speeds and over shorter distances. These in turn are also mechanisms that may have contributed to the increased jump height after flywheel stimulus, and could explain the differences found between both tested conditions.

This is the first study to analyse PAPE time course responses after an optimal intensity and low-volume isoinertial EO activity. However, flywheel resistance training with EO has been shown to be an effective CA to induce acute explosive enhancements between 3 and 9 minutes straight after the warm-up [22] in athletes [17–19, 23, 27] and young physically active people [20, 21, 28]. Indeed, sport-specific flywheel training seems to induce greater PAPE effects than traditional gravitational strength exercise [18]. Specifically in physically active people, Timon *et al.* [20] and Beato *et al.* [21] have reported small to moderate PAPE effects on vertical jump performance (SJ and CMJ height and concentric power, respectively) between 3 and 9 minutes after the CA. Even though they performed a higher volume (i.e., 3 sets of 6 repetitions), similar gains (between 6.8 and 15.6% in jump height and 4.3 and 8.4 in concentric peak power) were observed in comparison with our results. However, no significant enhancements were demonstrated after 12 minutes post-activation or longer rest in the aforementioned studies [20, 21]. This is probably due to exercise intensity, since they employed a low-intensity paradigm ( $0.029 \text{ kg}\cdot\text{m}^2$ ), which is generally prescribed to induce explosive neuromuscular adaptations, and it is lower than the inertia considered optimal for general conditioning ( $0.037 \text{ kg}\cdot\text{m}^2$ ) [29]. However, it is well known that greater moments of inertia can promote greater EO with the appropriate technique [16]. Recently, it has been shown that higher inertial loads with large volumes did not produce greater acute increases in explosive performance 3 and 6 minutes after preload exercise compared to a multiple-set and low-intensity approach [28]. Even though greater recruitment of higher order motor units, which may produce a greater postsynaptic potential and H-wave, is expected after higher EO exercises [28], the high neuromuscular fatigue induced by high-volume and high-intensity CA could have attenuated or delayed the PAPE responses. Indeed, when a single set of high, but not optimal, inertial load is prescribed, small to large PAPE effects were observed 6–8 minutes after activation [18, 23, 27]. Nevertheless, our results showed similar acute effects also at 12, 16 and 20 minutes after a similar warm-up which included optimal inertial load (i.e., exercise intensity) prescription during the flywheel CA. These

results suggest that lower total mechanical work undertaken at higher intensity may lead to greater PAPE effects, although these effects may be delayed due to longer transitory fatigue. This may be explained by the hypothesis that larger amounts of EO may induce more durable PAPE effects. In addition, as it occurs with gravitational resistances, highly experienced and stronger participants (the participants of this study showed greater values of concentric peak power in comparison with other similar studies [20]) may express greater potentiation levels after a single-set CA [4]. However, more research is needed to provide deeper insights into the physiological underpinning mechanisms which could explain these findings. Therefore, one of the limitations of this study is the lack of inclusion of other physiological parameters to provide more information on the underlying mechanisms (e.g., muscle temperature). Future research should include these parameters to investigate further the effects of EO on the PAPE mechanisms and to compare effects among different populations.

## CONCLUSIONS

In summary, a single set (i.e., 6 repetitions) of the half-squat flywheel exercise performed with the optimal concentric peak power intensity in physically active young men led to significant acute gains in CMJ jump height, CMJ concentric peak power and CMJ maximum concentric velocity at 4, 8, 12, 16 and 20 minutes after the CA. Thus, lower exercise volumes and higher intensity induced similar but longer duration PAPE effects compared to previous studies.

## Conflict of interest

The authors declare that there is no conflict of interest regarding the publication of this article.

## REFERENCES

1. Evans JW. Periodized Resistance Training for Enhancing Skeletal Muscle Hypertrophy and Strength: A Mini-Review. *Front Physiol.* 2019; 10:13.
2. Blazevich AJ, Babault N. Post-Activation Potentiation Versus Post-Activation Performance Enhancement in Humans: Historical Perspective, Underlying Mechanisms, and Current Issues. *Front Physiol.* 2019;10:1359.
3. Cuenca-Fernández F, Smith IC, Jordan MJ, MacIntosh BR, López-Contreras G, Arellano R, Herzog W. Nonlocalized Post-Activation Performance Enhancement (PAPE) Effects in Trained Athletes: A Pilot Study. *Appl Physiol Nutr Metab.* 2017; 42(10):1122–5.
4. Seitz LB, Haff GG. Factors Modulating Post-Activation Potentiation of Jump, Sprint, Throw, and Upper-Body Ballistic Performances: A Systematic Review with Meta-Analysis. *Sports Med.* 2016; 46(2):231–40.
5. McBride JM, Nimphius S, Erickson TM. The Acute Effects of Heavy-Load Squats and Loaded Countermovement Jumps on Sprint Performance. *J Strength Cond Res.* 2005;19(4):893.
6. Mina MA, Blazevich AJ, Tsatalas T, Giakas G, Seitz LB, Kay AD. Variable, But Not Free-Eight, Resistance Back Squat Exercise Potentiates Jump Performance Following a Comprehensive Task-Specific Warm-Up. *Scand J Med Sci Sports.* 2018;29: 380–392
7. Wilson JM, Duncan NM, Marin PJ, Brown LE, Loenneke JP, Wilson SMC, Jo E, Lowery RP, Ugrinowitsch C. Meta-Analysis of Postactivation Potentiation and Power: Effects of Conditioning Activity, Volume, Gender, Rest Periods, and Training Status. *J Strength Cond Res.* 2013; 27(3):854–9.
8. Schoenfeld BJ, Grgic J. Eccentric Overload Training: A Viable Strategy to Enhance Muscle Hypertrophy? *Strength Cond J.* 2018;40(2):78–81.
9. Suchomel TJ, Wagle JP, Douglas J, Taber CB, Harden M, Haff GG, Stone MH. Implementing Eccentric Resistance Training—Part 1: A Brief Review of Existing Methods. *J Funct Morphol Kinesiol.* 2019;4(2):38.
10. Bridgeman LA, McGuigan MR, Gill ND, Dulson DK. The Effects of Accentuated Eccentric Loading on the Drop Jump Exercise and the Subsequent Postactivation Potentiation Response. *J Strength Cond Res.* 2017; 31(6):1620–6.
11. Hughes JD, Massiah RG, Clarke RD. The Potentiating Effect of an Accentuated Eccentric Load on Countermovement Jump Performance. *J Strength Cond Res.* 2016;30(12):3450–5.
12. Ulrich G, Parstorfer M. Effects of Plyometric Versus Concentric and Eccentric Conditioning Contractions on Upper-Body Post-Activation Potentiation. *Int J Sports Physiol Perform.* 2017; 12(6):736–41.
13. Gołaś A, Maszczyk A, Zajac A, Mikołajec K, Stastny P. Optimizing post activation potentiation for explosive activities in competitive sports. *J Hum Kinet.* 2016;52(1):95–106.
14. Maroto-Izquierdo S, Fernandez-Gonzalo R, Magdi HR, Manzano-Rodríguez S, González-Gallego J, De Paz J a. Comparison of the Musculoskeletal Effects of Different Iso-inertial Resistance Training Modalities: Flywheel vs. Electric-motor. *Eur J Sport Sci.* 2019; 19(9):1184–94.
15. Maroto-Izquierdo S, García-López D, Fernandez-Gonzalo R, Moreira OC, González-Gallego J, de Paz JA. Skeletal Muscle Functional and Structural Adaptations After Eccentric Overload Flywheel Resistance Training: A Systematic Review and Meta-Analysis. *J Sci Med Sport.* 2017;20(10):943–51.
16. Carroll KM, Wagle JP, Sato K, Taber CB, Yoshida N, Bingham GE, Stone MH. Characterising Overload in Inertial Flywheel Devices for Use in Exercise Training. *Sports Biomech.* 2019; 18(4):390–401.
17. de Hoyo M, de la Torre A, Pradas F, Sañudo B, Carrasco L, Mateo-Cortes J, Domínguez-Cobo S, Fernandes O, Gonzalo-Skok O. Effects of Eccentric Overload Bout on Change of Direction and Performance in Soccer Players. *Int J Sports Med.* 2015;36(4):308–14.
18. Cuenca-Fernández F, López-Contreras G, Arellano R. Effect on Swimming Start Performance of Two Types of Activation Protocols: Lunge and YoYo Squat. *J Strength Cond Res.* 2015; 29(3):647–55.
19. Beato M, Bigby AEJ, De Keijzer KL, Nakamura FY, Coratella G, McErlain-Naylor SA. Post-Activation Potentiation Effect of Eccentric Everload and Traditional Weightlifting Exercise on Jumping and Sprinting Performance in Male Athletes. *PLOS ONE.* 2019;

- 14(9):e0222466.
20. Timon R, Allemanno S, Camacho-Cardenosa M, Camacho-Cardenosa A, Martinez-Guardado I, Olcina G. Post-Activation Potentiation on Squat Jump Following Two Different Protocols: Traditional vs. Inertial Flywheel. *J Hum Kinet.* 2019;69(1):271–81.
  21. Beato M, Stiff A, Coratella G. Effects of Postactivation Potentiation After an Eccentric Overload Bout on Countermovement Jump and Lower-Limb Muscle Strength. *J Strength Cond Res.* 2019.
  22. Beato M, McErlain-Naylor SA, Halperin I, Dello Iacono A. Current Evidence and Practical Applications of Flywheel Eccentric Overload Exercises as Postactivation Potentiation Protocols: A Brief Review. *Int J Sports Physiol Perform.* 2019;1–8.
  23. Cuenca-Fernández F, López-Contreras G, Mourão L, de Jesus K, de Jesus K, Zacca R, Vilas-Boas JP, Fernandes RJ, Arellano R. Eccentric Flywheel Post-Activation Potentiation Influences Swimming Start Performance Kinetics. *J Sports Sci.* 2019;37(4):443–51.
  24. McErlain-Naylor S, King M, Pain MTG. Determinants of Countermovement Jump Performance: A Kinetic and Kinematic Analysis. *J Sports Sci.* 2014; 32(19):1805–12.
  25. Prieske O, Maffiuletti NA, Granacher U. Postactivation Potentiation of the Plantar Flexors Does Not Directly Translate to Jump Performance in Female Elite Young Soccer Players. *Front Physiol.* 2018; 9:276.
  26. Tillin NA, Bishop D. Factors Modulating Post-Activation Potentiation and Its Effect on Performance of Subsequent Explosive Activities. *Sports Med.* 2009; 39(2):147–66.
  27. Cuenca-Fernández F, Ruiz-Teba A, López-Contreras G, Arellano R. Effects of 2 Types of Activation Protocols Based on Post-activation Potentiation on 50-m Freestyle Performance: *J Strength Cond Res.* 2018;1.
  28. Beato M, De Keijzer KL, Leskuskas Z, Allen WJ, Dello Iacono A, McErlain-Naylor SA. Effect of Post-activation Potentiation After Medium vs. High Inertia Eccentric Overload Exercise on Standing Long Jump, Countermovement Jump, and Change of Direction Performance. *J Strength Cond Res.* 2019 Jun 19. doi: 10.1519/JSC.0000000000003214.
  29. Martinez-Aranda LM, Fernandez-Gonzalo R. Effects of Inertial Setting on Power, Force, Work, and Eccentric Overload During Flywheel Resistance Exercise in Women and Men. *J Strength Cond Res.* 2017;31(6):1653–61.