

# Acute and Delayed Postactivation Performance Enhancement of a Portable Flywheel Isoinertial Device Versus Traditional Resistance Protocol on Countermovement Jump Performance

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## **ABSTRACT**

The aim of this study was to investigate the acute and delayed effects of two postactivation performance enhancement (PAPE) protocols on countermovement jump (CMJ) height without arm work. 16 strength-trained male participants from various team sports performed, in a single-group, non-synchronous crossover experiment, two different PAPE protocols: traditional resistance using free weights (TR) and resistance generated using an isoinertial flywheel device (FW). Familiarization sessions were conducted prior to the protocols. The TR protocol resistance was set at power maximum (P<sub>max</sub>) determined through diagnostic series of progressive loading. The FW protocol used an encoder to set resistances, and the resistance with the highest P<sub>max</sub> in concentric phase was selected. Each protocol consisted of 3 sets of 6 repetitions with a 2-minute rest interval. CMJ height was measured at baseline, 6 minutes, and 24 hours after the both PAPE protocols. The CMJ height significantly increased at 6 minutes after FW protocol ( $p < 0.01$ ) and after TR protocol ( $p < 0.05$ ) but did not significantly increase after 24 hours after both protocols ( $p < 0.05$ ). In conclusion the FW and TR protocol showed significant increases after 6 minutes but not after 24 hours in CMJ height. This suggests that FW and TR protocol can be an effective method for acutely inducing CMJ height improvements but not after 24 hours.

**Keywords:** Postactivation performance enhancement, countermovement jump, traditional resistance, isoinertial flywheel resistance, power maximum, strength training.

## INTRODUCTION

Muscle strength is a determinant of athletic performance and correlates with various athletic parameters such as jumps and sprints (Suchomel et al., 2016). Postactivation Performance Enhancement (PAPE) is currently understood as an acute increase in performance following prior high-intensity activation (Blazevich and Babault, 2019). While PAPE has been primarily associated with dynamic exercises involving higher contraction speeds (Cuenca-Fernández et al., 2017), it has also been observed following isometric contractions (Vargas-Molina et al., 2021; Koźlenia and Domaradzki, 2023 and 2024; Robbins and Docherty, 2005; Rixon et al., 2007; Piper et al., 2020; Pearson and Hussain, 2014; Tsolakis et al., 2011), electrical stimulation (Sari et al., 2022; Dote-Montero et al., 2021), and other activation methods (Prieske et al., 2020). Acute PAPE is the most commonly observed phenomenon in short-term performance enhancement (Fu et al., 2023; Gołaś et al., 2016; Tseng et al., 2021; Xie et al., 2022). This phenomenon has been observed using various training methods, including the use of isoinertial devices (Beato et al., 2023; Maroto-Izquierdo et al., 2020; McErlain-Naylor and Beato, 2021; Sañudo et al., 2020). Isoinertial flywheels (FW) are devices where the maximum speed during the concentric phase of movement results in an inertial torque of the flywheel, which provides high linear resistance during the subsequent eccentric phase of movement (De Hoyo et al., 2014; Gonzalo-Skok et al., 2017; Tous-Fajardo et al., 2016). The main advantage of using isoinertial devices, such as flywheel technology, lies in their ability to generate high eccentric loads due to the resistance produced by the inertia of the spinning wheel. While this does not inherently increase the total workload compared to traditional resistance training, it does shift the peak load towards the early phase of the eccentric contraction, which has been suggested to enhance neuromuscular adaptations (Tesch et al., 2017; Allen et al., 2021). These properties have been linked to both short-term and long-term performance improvements in athletes. (Beato et al., 2019; Gonzalo-Skok et al., 2017). Several studies have investigated the role of FW as a conditioning activity to elicit PAPE, examining its specific acute effects (Fu et al., 2023; Maroto-Izquierdo et al., 2020). Significant improvements in CMJ after FW training were demonstrated (Beato et al., 2019; de Keijzer et al., 2020; Maroto-Izquierdo et al., 2020). Only one set of high-intensity flywheel squats compared to one set of jumps (Maroto-Izquierdo et al., 2020) provide significant improvements in CMJ performance after 4, 8, 12, 16 and 20 minutes. But in other study, authors compared 1, 2 or 3 sets between each other and found out that no improvements after one but 2 or 3 sets of squats provided significant improvement in CMJ performance after 6 minutes (de Keijzer et al., 2020). Based on the findings mentioned above, it is evident that the body of research on acute PAPE is quite extensive and current. Regarding the delayed effects of PAPE, several studies (Cook et al., 2014; Raastad and Hallén, 2000; Saez Saez de Villarreal et al., 2007; Tsoukos et al., 2018) have examined PAPE with traditional free weight resistance to induce a delayed response lasting from 6 to 48 hours. Authors Cook et al. (2014) and Saez Saez de Villarreal et al. (2007) demonstrated an increase in vertical jump height after 6 hours using free weight training. Tsoukos et al. (2018) showed that low-volume but intense strength training (5 x 4 reps with 40% of 1RM) leads to delayed CMJ potentiation effect after 24 hours. Conversely, authors Raastad and Hallén (2000) found that low-volume training (70% of 1RM) can positively affect CMJ after 33 hours. Significant gains were

also recorded after 48 hours (Tsoukos et al., 2018). On the other side study where participants performed 5 sets of 10 repetitions with 60% of 1RM (total volume more than 2 times bigger) in squat discovered that squat jump height decreased after 24 and also 48 hours due to level of fatigue (Ishida et al., 2023). Latest study showed that such plyometric training can significantly increase CMJ height after 24 or 48 hours after 5 sets of 6 drop jumps from 52 centimeters with load corresponding to 20 % body mass (Souza et al., 2023). These findings showed that load in sets and total volume during training session can differently affect performance parameters in such jumps if we compared those studies. The most of these findings suggest that the effects of PAPE training with free weight resistance or plyometric training can persist for a longer period, from 24 to 48 hours (Souza et al., 2023, Tsoukos et al., 2018, Raastad and Hallén 2000) but it depends on other variables such a total volume in whole training session, which could affect performance (Ishida et al., 2023). This phenomenon may potentially enhance athletic performance in the following days. Further research is warranted to determine whether PAPE induced by isoinertial flywheels can persist longer and affect motor performance the following day. Currently, we do not know of studies where authors have investigated delayed PAPE using isoinertial flywheels for changes that would affect vertical countermovement jump parameters (CMJ).

## METHODS

A single-group, non-synchronous crossover experiment was used to assess the acute and delayed effects of two postactivation performance enhancement (PAPE) protocols: traditional resistance using free weights on a barbell (TR) and resistance generated using an isoinertial flywheel (FW). The effects of these protocols were measured through changes in vertical countermovement jump height without arm swing (CMJ). Before the experiment, each subject underwent 3 familiarization sessions with FW with 48-hour rest intervals between sessions (Sabido et al., 2018). During familiarization, subjects performed 3 sets of 10 repetitions at a resistance of  $0.079 \text{ kg}\cdot\text{m}^2$ . When setting resistances for the TR protocol, we followed the studies of Timon et al. (2019) and Beato et al. (2019), who used resistance at the level of power maximum (Pmax). To determine Pmax for each subject, we conducted diagnostic sets, gradually increasing the resistance by 5 to 10 kg per set, with a 2-minute rest interval between sets. The process continued until a decrease in performance was observed compared to the previous set. The highest achieved power output (W) at this point was considered Pmax. Power was derived from the force-velocity relationship, where velocity was recorded using FitroDyne PREMIUM, linear position transducer and calculated as power = force  $\times$  velocity. For the FW protocol, we used an encoder built directly into the device to set the resistances and selected the resistance with the highest achieved power in concentric phase of squat. We performed diagnostic sets on 3 resistances of isoinertial disks ( $0.079 \text{ kg}\cdot\text{m}^2$ ,  $0.104 \text{ kg}\cdot\text{m}^2$  and  $0.129 \text{ kg}\cdot\text{m}^2$ ). In the PAPE protocol, 3 sets of 6 repetitions with a 2-minute rest interval were performed (Beato et al., 2021a; Beato et al., 2021b; McErlain-Naylor and Beato, 2021). For each set of squats in the FW protocol, 2 additional repetitions were added with half the range and speed to ensure the maximum resistance speed of the flywheel in the following 6 repetitions of each set (2 + 6 repetitions per set) (Beato et al., 2023; Fu et al., 2023; Hall et al., 2024). The acute effect was

recorded 6 minutes and the delayed effect 24 hours after the PAPE protocols. The average value of three trials of CMJ test during baseline testing was compared to the average value of three trials of CMJ post-PAPE protocols (after 6 minutes and after 24 hours). The CMJ test was performed with 5 second pause between each trial. Each subject was asked to abstain from any high-intensity lower limb physical activity for at least 48 hours before testing. Participants were asked to refrain from any kind of physical activity focused on the lower limbs.

### ***Participants***

Sixteen strength-trained male volunteers with no health restrictions participated in the experiment (N = 16; age:  $23.1 \pm 1.6$  years; height:  $179.9 \pm 4.3$  cm; body weight:  $77.52 \pm 7.57$  kg; one-repetition maximum [1RM] squat to  $90^\circ = 132.61 \pm 19.12$  kg). Participants met the following inclusion criteria : being actively engaged in team sports (Football: n = 8; Ice Hockey: n = 5; Floorball: n = 2; Handball: n = 1), having a squat 1RM of at least 1.5 times their body weight (1RM/body mass =  $1.71 \pm 0.2$ ), and possessing a minimum of three years of regular strength training experience, training at least twice per week. Subjects were students of the faculty of sports science in the field of conditioning coaching and simultaneously active performance athletes in speed-strength sports. Those subjects who performed high-intensity strength training of the lower limbs less than 48 hours before the protocol were excluded from the research or had to start current protocol again after rest at least of 72 hours. If subjects had any serious injury in the last 6 months, could not be included in the study. They were informed about the possible risks and benefits associated with this research and confirmed informed consent to participate in the research.

### ***Design and Procedures***

Somatic Parameters – body height (cm) and body mass (kg) were measured (height - Stadiometer BSN170; weight – personal scale KERN MPI 200K-1S05). A manual goniometer was used to set the range of motion in the knee joint to  $90^\circ$  in the squat exercise. Each subject was provided with a solid obstacle with a hard landing in the lower squat position, constructed from weightlifting boxes, to ensure correct angles during its execution in TR. They were required to immediately begin the concentric phase upon touch. In the case of FW and contact with the expander, the expander was horizontally stretched at a precisely set height for each participant individually to  $90^\circ$  squat. This prevented a hard landing, allowing the subject to control their movement by feeling the contact with the expander. Each subject performed prescribed warm-up before testing. The warm-up consisted of 1 minute of jumping jacks, 1 minute of alternating jumps forward and backward, and a series of various dynamic exercises: 5 lunges on each lower limb, 10 bilateral squats, 5 vertical jumps with counter-movement without arm work (CMJ), and 5 unilateral forward bends to the lower limb (hamstring stretch). The entire warm-up lasted 4 minutes. After the warm-up, subjects had a 2-minute rest interval before performing the baseline CMJ. After the baseline measurement, subjects performed either the TR or FW protocol consisting of 3 sets and 6 repetitions of a half squat. A 2-minute rest interval was between sets. The resistance was set at the Pmax level in TR and at highest achieved power in FW protocol. This resistance was chosen based on previous studies that demonstrated the effectiveness of PAPE stimulation with resistance at the Pmax level (Timon et al., 2019; Beato et al., 2019). After the last set, each subject performed repeated CMJ measurements at the 6. minute and

then 24 hours after the baseline measurement. CMJ was repeated 3 times with 5 seconds rest between trials at each time point (baseline, 6 minutes and 24 hours). Subjects were instructed not to perform any physical activity during the subsequent 24 hours to avoid affecting the results.

### ***Traditional Resistance with Free Weight on a Barbell (TR)***

When setting the resistance using free weights, diagnostic series were performed to determine the power maximum (P<sub>max</sub>) in the squat to a 90° angle in the knee joint using the Fitro Dyne PREMIUM device (TR resistance: 125.31 ± 21.25 kg; P<sub>max</sub>: 1182.32 ± 203.85 W). Each subject had the resistance on the free barbell gradually increased by 10 kg or later by 5 kg, depending on the situation. This process continued until the resistance reached a point where the power dropped compared to the previous series. This previous resistance is presented as the absolute weight of the additional load at which the highest P<sub>max</sub> was achieved. We performed 2 repetitions and presented the repetition with the highest power. During each repetition in the series, subjects were instructed to perform the exercise with maximum effort in the concentric phase of the movement. The main research examiner provided assistance during the exercise. Positioned behind the subject, the examiner helped lift the resistance if necessary. At the contact point in the lower position during squats with TR, all participants experienced a firm landing. Rubberized plates were used to ensure that each subject consistently reached a precise 90° knee joint angle. They were required to immediately begin the concentric phase upon touch.

### ***Resistance Generated Using an Isoinertial Flywheel (FW)***

The FW protocol was carried out on the HandyGym™ device (Vigo, Pontevedra, Spain), model PRO with a built-in encoder to monitor the load progress. We conducted the protocol with a resistance with the highest achieved power in concentric phase. The main protocol consisted of 3 sets of 6 repetitions with a 2-minute rest interval. Prior to the protocol, each subject underwent a familiarization phase with the device. Based on Fu et al. (2023) and Beato et al. (2020), subjects completed 3 familiarization sessions with a 48-hour interval between sessions. The familiarization phase included 3 sets of 10 repetitions at a resistance of 0.079 kg·m<sup>2</sup> with a 2-minute rest interval. The higher number of repetitions during familiarization was implemented to allow participants to perform more repetitions at a lower resistance, ensuring better adaptation and familiarization with the device before proceeding to the main protocol. After familiarization, diagnostic series were performed at resistances of 0.079 kg·m<sup>2</sup>, 0.104 kg·m<sup>2</sup>, and 0.129 kg·m<sup>2</sup> to set the resistances on FW. Each diagnostic series consisted of 3 repetitions. To determine the P<sub>max</sub>, the device itself, equipped with an encoder to monitor the load progress, was used. The device was connected via Bluetooth to the examiner's tablet, which had the appropriate software for load monitoring (HANDYGYM Athletic performance version 1.1.0. 2023). For each repetition, the encoder provided immediate feedback with power maximum (P<sub>max</sub>). Participants reached their highest P<sub>max</sub> in concentric phase at the 0.104 kg·m<sup>2</sup> and 0.129 kg·m<sup>2</sup> resistance (FW resistance: 0.117 ± 0.013 kg·m<sup>2</sup>; P<sub>max</sub>: 1130.86 ± 279.18 W) determined from the diagnostic series. This aimed to ensure the most comparable resistance between the two experimental protocols. For safety in FW, due to the increasing eccentric overload depending on the preceding concentric phase of the movement, an expander was chosen for contact at the lower position with a 90° angle in the knee joint.

### ***Postactivation Performance Enhancement Protocol (PAPE)***

Subjects performed the PAPE protocol, which consisted of 3 sets and 6 repetitions with 2 more repetitions in the case of FW (Fu et al., 2023) with a 2-minute rest interval between sets. Subjects were not allowed to perform any active rest techniques to mitigate the effects of fatigue (de Keijzer et al., 2020; Hall et al., 2024). The protocol order was randomly chosen by coin toss. Each subsequent PAPE protocol session was conducted with a 72-hour interval between sessions (Monteiro et al., 2019).

### ***Counter-Movement Vertical Jump without Arm Work (CMJ)***

Performance in the CMJ test was recorded using the OptoJumpNext device (version 1.12.23). All CMJ performances were conducted with subjects' hands firmly placed around their hips to prevent arm swing and isolate the work of the lower limbs. Each subject was individually instructed to perform each jump repetition with maximum effort. To ensure consistency and minimize learning effects, a familiarization session for CMJ was conducted. After each familiarization session for the FW, participants performed 3×3 CMJ trials, completing a total of three familiarization sessions before the main testing. During the baseline testing before the PAPE protocol, subjects always performed 3 repetitions of vertical jumps with a 5-second rest interval, responding to the examiner's word «hop.» After the PAPE protocol, subjects performed 3 repetitions of maximum effort CMJ with a 5-second rest interval between repetitions after 6 minutes and again after 24 hours. The mean value of the three trials was calculated and used for comparison. During the rest interval post-PAPE protocol, no active recovery techniques or preparatory vertical jumps were allowed. The range of motion was ensured by soft contact with the expander at a 90° angle in the knee joint, and subjects were instructed to keep their feet in dorsiflexion during the flight phase of the CMJ movement. The reliability coefficient between baseline tests of TR and FW protocols was high (Intraclass correlation coefficient (ICC) = 0.94; 95% confidence interval (CI) = 0.84–0.98; standard error of measurement (SEM) = 0.52 cm; smallest real difference (SRD) = 1.14 cm).

### ***Statistical Analysis***

The statistical analysis was performed using IBM SPSS Statistics, version 27.0 (IBM Corp., New York, USA). We used the Shapiro-Wilk test for normality of data distribution. One-way ANOVA with repeated measures and Bonferroni post hoc test were used to determine the potentiation effect of FW and TR protocols on the dependent variable (height [cm] in CMJ). The factors were three time points (baseline, 6 minutes, and 24 hours) and two protocols (traditional and inertial). The interaction effect between time and protocol was assessed using the multivariate criterion of Pillai's trace. The reliability of the input data was determined using the intraclass correlation coefficient (ICC) with a 95% confidence interval between two testing sessions. The ICC was calculated between the input data of the traditional protocol and the input data of the inertial protocol. In addition to the ICC, we evaluated the standard error of measurement (SEM) and the smallest real difference (SRD) (Timon et al., 2019; Beckerman et al., 2001) SEM was calculated:  $SEM = \sigma \times \sqrt{1 - r}$  ( $\sigma$  = standard deviation;  $r$  = reliability coefficient); SRD was calculated:  $1.96 \times \sqrt{2}$  (2 because of the difference of two variance)  $\times$  SEM (Beckerman et al., 2001). Practical significance, or Effect Size (ES), was assessed using the Omega Squared test, which specifically refers to the time effect. To interpret the Omega Squared values, we followed the scale: 0.01 as a small effect, 0.06 as

a medium effect, and 0.14 or more as a large effect of practical significance. The level of statistical significance was set at  $p < 0.01$  and  $p < 0.05$  with a 95% confidence level. For descriptive statistical methods, we used means and standard deviations (SD).

## RESULTS

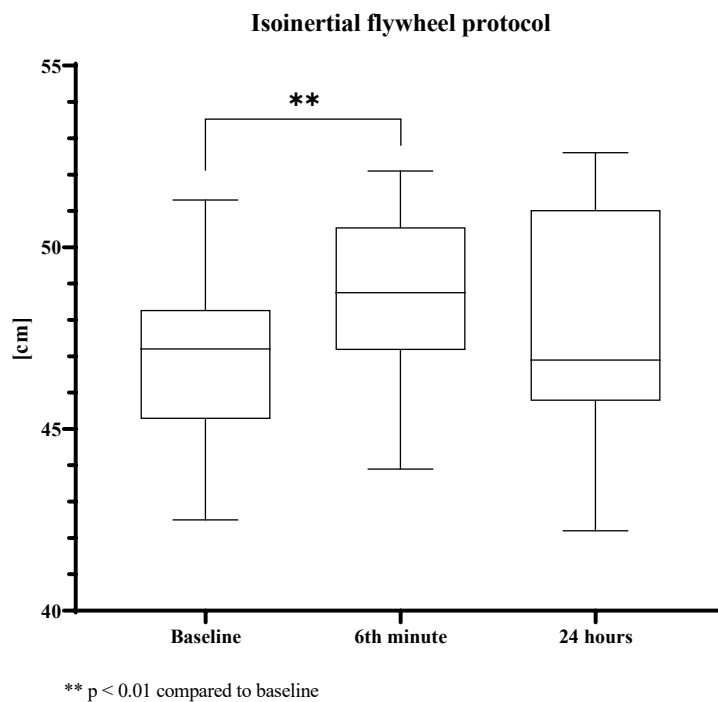
Table 1 displays the acute and delayed effects of PAPE on the dependent variable (height) in CMJ using FW and TR protocols. The values presented in the table represent the mean values calculated from three CMJ trials performed at each time point.

**Table 1. Acute and Delayed Effects of PAPE in CMJ**

Protocol	Variable	Baseline	6 minutes	24 hours	p value	$\omega^2$
FW	Height [cm]	47.01 ± 2.26	48.90 ± 2.20 *	47.99 ± 3.13	0.11	0.17
TR	Height [cm]	46.94 ± 2.15	48.54 ± 2.78 *	47.89 ± 3.14	0.13	0.15

\* Statistically significant difference compared to baseline ( $p < 0.05$ )

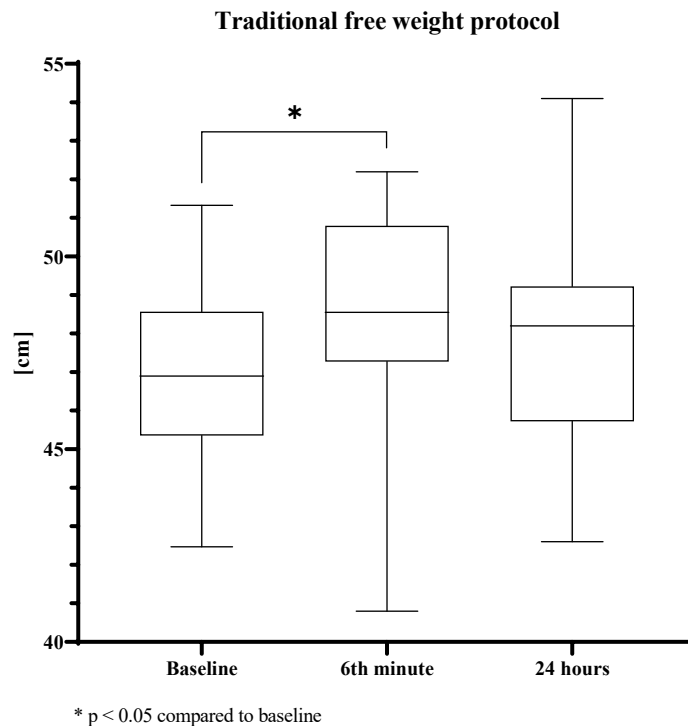
The FW protocol (Figure 1) was significantly effective in repeated measurements after 6 minutes and after 24 hours ( $F = 2.970$ ;  $p > 0.05$ ). The effect size, Omega squared ( $\omega^2$ ), was large (0.17). Bonferroni’s post hoc test showed statistically significant increases after 6 minutes ( $p < 0.01$ ). After 24 hours increases in CMJ were not statistically significant ( $p > 0.05$ ).



**Figure 1. Isoinertial flywheel protocol enhancing CMJ performance after 6 minutes and 24 hours**

In the TR protocol (Figure 2), no significant increases were observed in repeated measurements ( $F = 2.577$ ;  $p > 0.05$ ). The effect size  $\omega^2$  was large (0.15). Bonferroni’s post hoc showed statistically

significant increases after 6 minutes ( $p < 0.05$ ) and did not show statistically significant increases after 24 hours ( $p > 0.05$ ).



**Figure 2. Traditional free weight protocol enhancing CMJ performance after 6 minutes and 24 hours**

Table 2 displays the reliability coefficient ICC between the baseline of CMJ of FW and TR protocols. ICC coefficient was high (0.94 %). The 95 % confidence interval (CI) was 0.84 – 0.98. The standard error of measurement (SEM) was 0.52 cm, and the smallest real difference (SRD) was 1.43 cm.

**Table 2. Inter-class correlation coefficient, 95 % confidence interval, standard error of measurement, smallest real difference of variable height [cm] of CMJ comparing baselines of protocols FW and TR**

	ICC	95 % CI	SEM	SEM%	SRD	SRD%
Height of CMJ	0.94 %	0.84 – 0.98 %	0.52 cm	1.07 %	1.43 cm	3.05 %

## DISCUSSION

This study is the first to investigate the delayed effects of PAPE using an inertial device on changes in CMJ height levels. The observed delayed effect was after 24 hours. The results suggest that CMJ height was not significantly increased 24 hours after the FW or TR protocol. We also investigated the acute effects of PAPE at 6. minutes. The results of the acute PAPE effect showed a significant improvement in CMJ height after 6 minutes after both FW and TR protocols.

The inertial flywheel is a device that, by shifting the load intensity towards the beginning of the eccentric phase, can influence subsequent performance in the vertical jump without increasing the total workload (Beato et al., 2023; Timon et al., 2019). The acute effects of PAPE have been

relatively extensively studied in recent years using the FW (Beato et al., 2021a; de Keijzer et al., 2020). The most observed time windows of the PAPE effect were between 3–9 minutes (Beato et al., 2021a; Beato et al., 2021b; Xie et al., 2022). The literature review suggests that 6 minutes has been identified in previous studies as an effective time point for observing PAPE effects (de Keijzer et al., 2020; McErlain-Naylor and Beato, 2021). These studies compared multiple time points and found significant effects at 6 minutes, which informed our decision to measure CMJ performance at this time. Our findings demonstrated significant increases in CMJ height after 6 minutes, aligning with previous research. The authors de Keijzer et al. (2020) recorded improvements after 6 minutes rather than after 3 minutes. This claim is also supported by other authors (Beato et al., 2021b). Beato et al. (2021b) demonstrated significant improvements in CMJ height from 3 minutes ( $BF_{10} = 5.1$ , indicating moderate evidence in favor of the effect) up to 6 minutes ( $BF_{10} = 91.9$ , indicating very strong evidence in favor of the effect). These findings align with our results, as previous studies have identified 6 minutes as a key time point for observing PAPE effects. Based on these findings, a 6 minutes delay appears to be an effective time frame for enhancing CMJ performance.

Based on the findings of several authors, performing 3 sets of 6 repetitions of squats to 90° knee flexion has been identified as an effective protocol for potentiating performance in the CMJ (Beato et al., 2023; Beato et al., 2021a; Beato et al., 2021b). Some studies have examined the effects of only one set (de Keijzer et al., 2020; Maroto-Izquierdo et al., 2020) or two sets of 6 repetitions (de Keijzer et al., 2020). According to de Keijzer et al. (2020), greater potentiation effects are observed when performing 2 or more sets using FW resistance. While our results align with these findings, our study did not compare different set volumes; therefore, we cannot conclude whether additional or fewer sets would have yielded a greater effect.

Regarding the rest interval, we relied on several studies where the authors mostly used a 2 minutes (Beato et al., 2023; McErlain-Naylor and Beato, 2021) or 3 minutes (Timon et al., 2019) rest interval. The finding by Timon et al. (2019), where the authors demonstrated significant changes in the vertical jump performance of squat jump (SJ) only in the FW protocol, but did not record significant increases in the TR protocol, only confirms the effectiveness of the 2 minutes rest interval, after which the authors recorded significant improvements in the CMJ test (Beato et al., 2021a; Beato et al., 2021b).

The magnitude of the resistance of the inertial flywheel represents a great variability in setting the resistance in training. For example, Beato et al. (2023) and de Keijzer et al. (2020) used a resistance of 0.029 kg·m<sup>2</sup> in their studies. Xie et al. (2022) showed the greatest increases at 3, 6, and 9 minutes after using a higher resistance of 0.075 kg·m<sup>2</sup>. Beato et al. (2020) processed a review of 7 studies where they used a resistance range from 0.03 kg·m<sup>2</sup> to 0.88 kg·m<sup>2</sup>. Multiple resistances can be used in training with the FW, with previous studies reporting values up to 0.11 kg·m<sup>2</sup> (Beato and Iacono, 2020). However, in our study, individualized resistance values were used based on diagnostic testing, where some participants performed with 0.104 kg·m<sup>2</sup> or 0.129 kg·m<sup>2</sup>, determined as their Pmax value. In the study by Maroto-Izquierdo et al. (2021), they used an individualized optimal moment of inertia ( $0.083 \pm 0.03$  kg·m<sup>2</sup>) in PAPE using only one set of 6 repetitions. In our study, we used a resistance with the highest achieved power from diagnostic sets of three different resistances (0.079 kg·m<sup>2</sup>, 0.104 kg·m<sup>2</sup>, and 0.129 kg·m<sup>2</sup>). We also investigated the effects of PAPE

using free weight. The resistance in this case was set at the Pmax level (Timon et al., 2019). To have comparable resistances in both protocols, the resistance of each subject had to correspond to the movement speed in the concentric phase of the free weight resistance (Pmax). Sanudo et al. (2020) implemented such a resistance setting system in their work. They set the resistance on the FW until it reached a speed of  $0.45 \text{ m}\cdot\text{s}^{-1}$ , which represented the speed at 90 % of 1 RM on the free weight.

In our study, we investigated the acute effects of PAPE using two protocols, FW and TR, in the CMJ test (Timon et al., 2019; Beato et al., 2019). Timon et al. (2019) found that the FW protocol was able to significantly influence the potentiation of vertical jump performance at 4 and 8 minutes, while the TR protocol was unable to improve vertical jump height. These claims are not confirmed by the author Beato et al. (2019), who demonstrated improvements using both protocols in the CMJ between 3 and 7 minutes and recommend their use to stimulate PAPE. In our study, our subjects significantly improved after 6 minutes of acute PAPE, which confirms the findings of several authors (Beato et al., 2023; McErlain-Naylor and Beato, 2021; Beato et al., 2019; Xie et al., 2022).

Delayed potentiation has been investigated so far using free weight resistance. The most observed times were 6 hours (Cook et al., 2014; Saez Saez de Villarreal et al., 2007), 24 and 48 hours (Tseng et al., 2021; Tsoukos et al., 2018) after performing the resistance protocol. In our study, we focused on PAPE after 24 hours and monitored changes in CMJ height.

Tsoukos et al. (2018) demonstrated a  $5.1 \pm 1.0 \%$  improvement using a resistance at the level of 40 % of 1RM. In our study, we used a resistance within the TR protocol at the Pmax level (Timon et al., 2019; Beato et al., 2019). Our subjects were unable to improve significantly after FW and TR protocol. The improvements after TR of  $2.04 \pm 5.02 \%$  and after FW of  $2.08 \pm 4.87 \%$  was not statistically significant after 24 hours. This could have been due to the difference in the volume and intensity of the load. The intensity of the load at the Pmax level (Timon et al., 2019) does not seem to be entirely adequate for improving the CMJ after 24 hours within the FW and TR protocol. previous research has shown, PAPE effects are highly intraindividual, and this could have been the reason for such a large % SD (FW: 4.87 %; TR: 5.02 %). Our findings support those by Tseng et al. (2021). They examined the effects of an eccentric-enhanced protocol (105% of 1RM) compared to a concentric-only protocol (80% of 1RM) (AEL) and a classic resistance protocol at 85% of 1RM. Within the delayed effects of the AEL protocol, CMJ height did not improve (Tseng et al., 2021). They recorded a decrease of approximately 1 cm after 24 hours and more than 3 cm after 48 hours.

In our study, we observed an average improvement of  $0.95 \pm 2.39 \text{ cm}$  after 24 hours for the FW and  $0.97 \pm 2.27 \text{ cm}$  for the TR, but this change was not statistically significant. Based on our results, in the case of Tseng et al. (2021), their resistance was likely higher compared to our resistance at the Pmax level in the TR. On the other hand, if we compare their AEL protocol as an equivalent to our FW protocol (due to eccentric overload), we can conclude that our FW protocol was not as effective as their AEL protocol. The mechanism behind our observed improvement, albeit statistically insignificant, remains a topic for future research, as the findings of Tseng et al. (2021) could have been influenced by the level of fatigue, whereas in our study, no decrease in performance was observed. On the other hand, a study by Ishida et al. (2023), where participants performed 5 sets of 10 repetitions at 60% of 1RM (resulting in a total training volume more than twice as large as in our study), found that squat jump height decreased after 24 and 48 hours due

to accumulated fatigue. These findings further support the hypothesis that the level of fatigue plays a critical role in the delayed effects of different training protocols on vertical jump performance.

## CONCLUSION

Our findings align with previous studies confirming that 6 minutes is an effective time point for observing PAPE effects (de Keijzer et al., 2020; McErlain-Naylor and Beato, 2021). However, unlike some previous research, we did not observe a significant improvement 24 hours post-PAPE, leaving an open question as to why this effect was not present in our study. Further research is needed to explore potential reasons for this discrepancy. It is possible that the applied stimulus was not sufficient to induce a lasting effect, or conversely, that the stimulus was too large, leading to only small improvements that were difficult to detect statistically. Understanding these factors will be essential for optimizing PAPE protocols to enhance long-term performance adaptations, particularly in the context of competition, which may take place one or two days after the conditioning stimulus.

## LIMITATIONS

Our study had several limitations that could have influenced the results. The selection of subjects was not a specialized group for a particular sports specialization. The research included amateur or performance athletes from various team sports. Another limitation was the Handy Gym device itself, which is not a commonly used and studied inertial device in studies. Compared to other devices, it is a cheap equivalent to other devices. We were unable to quantify the magnitude of the Handy Gym resistance precisely. The encoder built into the device is not yet a reliable tool for recording the load progression within the concentric-eccentric phase of movement, so we cannot precisely say how great the overload of eccentric phase was. We decided to use this device mainly because it is small and portable compared to other devices and has not yet been studied in studies. In the future, we plan to conduct similar research on a specific sample of a particular sports specialization, which could make our work more beneficial in sports practice.

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*All authors contributed to the study's conception and design. Material preparation, data collection, and analysis were performed by all authors. The first draft of the manuscript was written by the first author, and all authors provided feedback on previous versions of the manuscript. All authors read and approved the final manuscript.*

## ETHICS APPROVAL AND CONSENT TO PARTICIPATE

*All procedures performed in studies involving human participants were in accordance with the ethical standards of the institutional and/or national research committee and with the 1975 Helsinki declaration and its later amendments or comparable ethical standards. Informed consent was obtained from all individual participants included in the study.*

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