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Research article

Post-activation Performance Enhancement of Countermovement Jump after Drop Jump versus Squat Jump Exercises in Elite Rhythmic Gymnasts

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Abstract
Drop jump (DJ) and squat jump (SJ) exercises are commonly used in rhythmic gymnastics training. However, the acute effects of DJ and SJ on countermovement jump (CMJ) performance have not been investigated. This study aimed to verify the post-activation performance enhancement (PAPE) responses induced by DJ and SJ with optimal power load and evaluate the relationship between peak PAPE effects and strength levels. Twenty female rhythmic gymnasts completed the following exercises in a randomized order on three separate days: 6 repetitions of DJs; 6 repetitions of SJs with optimal power load; and no exercise (control condition). Jump height was assessed before (baseline) and at 30 seconds and 3, 6, and 9 minutes after each exercise. DJs significantly improved jump height by 0.8 cm (effect size (ES) = 0.25; *P* = 0.003) at 30 seconds post-exercise compared with baseline. Jump height significantly decreased by -0.35 cm (ES = -0.14; *P* = 0.021) at 9 minutes after the control condition. SJs significantly improved jump height by 1.02 cm (ES = 0.36; *P* = 0.005) at 9 minutes post-exercise compared to the control condition. Jump height and relative back squat one-repetition maximum were positively related after performing DJs (r = 0.63; *P* = 0.003) and SJs (r = 0.64; *P* = 0.002). DJ and SJ exercises effectively improved countermovement jump height. DJ improved jump height early, while SJ produced greater potentiation effects later. Athletes with a higher strength level benefited the most from these exercises.

Key words: Optimal power load, plyometric, warm-up, post-activation performance enhancement.

Introduction

Rhythmic gymnastics (RG) is an Olympic sport involving graceful and rhythmic movements with or without a light apparatus, accompanied by music. Jumping ability is essential for RG performance (Di Cagno et al., 2009). Judges evaluate jumps based on a specific shape during flight and sufficient height to display the corresponding shape (FIG, 2022). Higher jumps are more likely to achieve the desired shape, increasing the chances of receiving high scores. Thus, developing lower limb power is crucial for RG athletes.

Plyometric exercises, such as jumps, hops, and bounds, are commonly utilized to improve lower limb performance via the stretch-shortening cycle (Ramirez-Campillo et al., 2018). Plyometric exercises improve jump performance in RG athletes (Cabrejas et al., 2023; Dallas et al., 2020; Nitzsche et al., 2022). For example, Cabrejas et al. (2023) compared the effects of 8 weeks of integrated core and plyometric training with traditional RG training (without plyometric training) on countermovement jump (CMJ) performance; the height of unilateral and bilateral CMJs increased significantly after the integrated core and plyometric training, while no differences in CMJ height were observed after traditional RG training. Although the chronic training effects of plyometric exercises on jump performance have been extensively studied in RG athletes (Cabrejas et al., 2023; Dallas et al., 2020; Nitzsche et al., 2022), the acute effects of plyometric exercises on post-activation performance enhancement (PAPE) are unclear.

PAPE proposed that voluntary muscle contractions may lead to acute athletic performance enhancement without twitch verification in training and competition settings (Boullosa et al. 2020b; Wilson et al., 2013). Several potential mechanisms underpin PAPE, including myosin light chain phosphorylation, muscle temperature, blood flow, muscle activation, and muscle–tendon stiffness (Blazevich and Babault, 2019). The drop jump (DJ) is a popular plyometric exercise involving rapid stretch-shortening cycle action (duration ≤ 250 ms) (Ramirez-Campillo et al., 2013). Studies focused on the physiological and neuromuscular effects of DJ on PAPE demonstrated significant improvements in cycling performance (de Poli et al., 2020) and repeated sprint performance (Zagatto et al., 2022b), but no changes in muscle activity were observed during performance testing. De Poli et al., (2020) demonstrated that increased peak force evoked by supramaximal stimulation, greater glycolytic energy and higher anaerobic capacity contributed to PAPE. In addition, Chen et al. (2013) reported that DJ significantly improved CMJ height within a 2-minute rest interval in male volleyball players. To date, there are few study to investigate the effects of DJ on PAPE in female athletes. In this regard, only one study (Boullosa et al., 2020a) showed that five repetitions of DJ induced a "possible" improvement in 1000-m performance in male athletes, but a "possible" worsening in performance in female athletes. Considering that DJ exercise is widely used in RG training sessions and research on female athletes is limited, we investigated the effects of DJ on PAPE in female RG athletes.

Optimal power load (OPL) has recently gained attention as an approach to inducing PAPE in strength training (Loturco et al., 2022). Performing three sets of six repetitions of squat jumps (SJs) with OPL significantly

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improved CMJ height after 4 and 8 minutes compared to baseline (Dello Iacono et al., 2020a). The determination of OPL is based on individual's load-power relationship, with the goal of maximizing muscle power output. The loads associated with OPL during lower-body resistance exercises, which are lower than the commonly utilized loads (i.e., 85% 1RM) in PAPE protocols, typically range from 30% to 70% of the one-repetition maximum (1RM) (Soriano et al., 2015). Resistance exercises with heavy loads may result in slower muscle contractions and a greater acute increase in testosterone and growth hormone levels, causing muscle hypertrophy (Ratamess et al., 2009). RG athletes are typically slender and require a high jumping ability. Thus, training should improve muscle power output without causing muscle hypertrophy. Excessive hypertrophy is unsuitable for RG athletes due to the possible loss of reactivity. Therefore, the use of OPL may be an appropriate training strategy for inducing PAPE in RG athletes.

Zagatto et al. (2022a) compared the PAPE effects of DJ and heavy sled towing and showed that only DJ positively affected sprinting performance. To the best of our knowledge, no study compared the effects of DJ and SJ with OPL on PAPE in RG athletes. Strength levels may also affect PAPE (Seitz and Haff, 2016) and warrant further investigation. The purpose of this study was to investigate the effects of DJ and SJ with OPL on CMJ performance in elite RG athletes and determine whether the PAPE is related to strength level. We hypothesize that both DJ and SJ with OPL will improve CMJ performance, and PAPE will be higher in athletes with a higher strength level.

Methods

Participants

Twenty female elite rhythmic gymnasts (age: 18.25 ± 2.55 years; height: 168.4 ± 5.32 cm; body mass: 51.42 ± 4.66 kg; body mass index (BMI): 18.11 ± 1.01 kg/m^2; back squat relative 1RM: 1.32 ± 0.19; RG training experience: 10.45 ± 1.39 years) participated in this study. Six of the athletes competed at the international level and the remaining athletes competed at the national level. The inclusion criteria were as follows: 1) no neuromuscular disorders, 2) no lower-limb injuries for at least six months prior to the study; and 3) participated in regular gymnast-specific training and conditioning training for at least 12 months prior to the study. All participants underwent regular training with 12 sessions (6 days) per week, including 10 4 - 6-hour gymnast-specific sessions and 2 conditioning sessions. Conditioning training sessions included strength training, power exercises, jump exercises, and sprinting. All participants were familiar with the testing exercises performed in this study. The study was conducted after the November 2023 National Championships. Coaches and participants were informed about the study procedures, benefits, and potential risks and signed an informed consent. Parental consent was required for participants under 18 years old. The study was approved by the Chengdu Sport University Science Research Ethics Committee and conducted in accordance with the Helsinki Declaration.

Study design

A randomized crossover design was employed to investigate the acute effects of DJ and SJ with OPL on CMJ performance. Participants completed 2 sessions to familiarize them with the back squat, SJ, DJ, CMJ, and study procedures. After the familiarization sessions, the back squat 1RM and the OPL in the SJ exercise were assessed in two separate sessions. During the experimental sessions, participants performed a standardized warm-up and baseline CMJ assessment followed by DJ SJ with OPL, or no exercise (control condition) in a randomized order on three separate days. The CMJ was re-assessed after 30 seconds and 3, 6, and 9 minutes of recovery (Figure 1). All sessions were separated by at least 72 hours.

Back squat 1RM assessment

Before the assessment, participants performed a standardized warm-up consisting of 400-meter low-intensity running followed by six dynamic stretching exercises (e.g., walking knee lift and inverted hamstring stretch). The warm-up was identical in all sessions. Each dynamic stretching movement performed 10 repetitions, gradually increasing the range of motion. Participants were then instructed to perform 5, 3, and 2 repetitions at 50%, 70%, and 80% of the estimated 1RM, respectively. Three minutes of recovery was provided. Then, participants completed 3 - 4 attempts to achieve their 1RM with a correct back squat technique. Five minutes of recovery was allowed. The eccentric and concentric phases of the back squat were executed with a self-controlled tempo. Participants were instructed to position their feet shoulder-width apart with their toes pointed slightly outward, and to squat to a 90° knee angle. The 1RM value was normalized to the participants' body mass (i.e., relative strength) (Byrne et al., 2020).

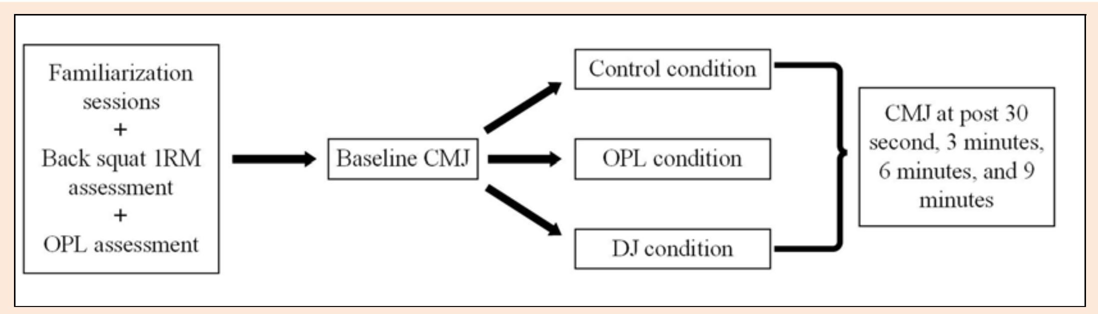

Figure 1. Schematic of the study design. RM = repetition maximum; OPL = optimal power load; DJ = drop jump; CMJ = countermovement jump.

OPL assessment

The OPL in the SJ exercise was assessed on a power rack. After the standardized warm-up, SJ warm-up sets with progressively increased loads were performed as previously described (Loturco et al., 2022). Briefly, participants performed three repetitions at maximal velocity with each load, starting at 40% of their body mass. The load was gradually increased by 10% of body mass until a clear decrease in mean power was observed. Four-minute intervals were given between loads to provide adequate recovery. For the SJ, participants were asked to position their feet shoulder-width apart and hold the bar on their shoulders. A knee flexion of approximately 90° was performed and held for 2 seconds. After a command, the participants jumped as high as possible without the bar leaving their shoulder. Two researchers supervised the assessment procedure from both sides of the power rack and provided verbal encouragement.

A GymAware powertool transducer (Kinetic Performance Technology, Canberra, Australia) was positioned on the floor at the right back side of the power rack to collect mean power data. Participants were instructed to lift the bar and took one or two steps backward to ensure that the cable was perpendicular to the ground. The OPL was determined based on the highest mean power measured during the successive trials. The mean power was normalized to the participants' body mass. The normalized mean power value was 6.9 ± 1.3 W/kg.

Countermovement jump assessment

CMJ height was determined by the flight time using the Optojump photoelectric system (Microgate, Bolzano, Italy) at a sampling frequency of 1000 Hz. The Optojump photoelectric cells consist of two parallel bars, which are placed approximately 1 meter apart. Participants performed two submaximal CMJ at 50% of their perceived maximal effort. One minute later, 3 baseline CMJs separated by 15-second rest periods were assessed. The procedure was repeated for each time point after the exercise. Researchers provided verbal encouragement throughout the assessments. Participants started in a standing position with hands on their hips. They executed a rapid countermovement action to a self-selected depth immediately followed by a forceful vertical jump, gradually extending the legs. The best value of 3 jumps was retained for the analysis (Zagatto et al., 2022b).

Postactivation performance enhancement protocols

The DJs, SJs with OPL, or no exercise (control condition) were completed on 3 separate days in a randomized order. Participants completed 6 repetitions of SJ with OPL and 6 repetitions of DJ with 15 seconds of recovery between the repetitions. The box height was determined by measuring the distance from the participant's lateral femoral condyle on their leg to the floor (Chattong et al., 2010) to ensure that the DJ intensity was standardized for all individuals. The mean box height was 50.5 ± 2.3 cm. During the DJ, participants were instructed to place their hands on their hips and step off from the box with the leading leg straight to avoid any initial upward propulsion, and to jump vertically at a maximal height as quickly as possible. Two researchers supervised the exercises and provided verbal encouragement. During the control condition, participants sat for the same duration as the PAPE exercises after completing the baseline CMJ test. All testing sessions were performed under consistent indoor temperature conditions (20°C - 25°C).

Statistical analyses

All data are expressed as means with standard deviations (± SD) and were analyzed using SPSS statistical software (version 25.0. SPSS Inc., Chicago, IL, USA). The intraday reliability of the 3 baseline CMJ assessments in the control session was determined using the coefficient of variability (CV). The interday reliability of the best baseline CMJ assessment in all conditions was assessed using the intraclass correlation coefficient (ICC). Data normality and the assumption of sphericity were verified with the Shapiro-Wilk and Mauchly's tests, respectively. A two-way (3 conditions × 5 time points) repeated measures analysis of variance (ANOVA) was used to compare jump height. Baseline and individual peak PAPE response were compared using two-way (3 conditions × 2 time points [baseline; post best value]) ANOVA. If sphericity was violated, the Greenhouse-Geisser correction was used to adjust the degrees of freedom. If significant main effects or interactions were detected, post hoc pairwise comparisons were conducted using Bonferroni adjustments. The range of mean differences was estimated using 95% confidence intervals. Effect size (ES) was calculated using Cohen's *d* to determine the magnitude of PAPE. Thresholds for qualitative descriptors of ES were considered trivia at ≤ 0.2, small at 0.2 - 0.49, moderate at 0.5 - 0.79, and large at > 0.8 (Cohen, 1988). The relationship between relative back squat 1RM and individual peak PAPE responses and the time to elicit peak PAPE were assessed using Person correlation analyses. Thresholds for qualitative descriptors of relationship were considered trivial at 0.0 - 0.09, small at 0.10 - 0.29, moderate at 0.30 - 0.49, large at 0.50 - 0.69, very large at 0.70 - 0.89, nearly perfect at 0.90 - 0.99, and perfect at 1.0 (Hopkins et al., 2009). Statistical significance was set at p < 0.05.

Results

All data were normally distributed. The measurement reliability was high for jump height (CV = 3.9%; ICC = 0.88). A statistically significant interaction effect was detected for jump height ($F_{4.527,\,86.02} = 5.063$; *P* = 0.001; $\eta^2 = 0.21$). Post hoc analyses revealed that jump height significantly decreased at 9 minutes postexercise (-0.35 cm [-0.038, -0.662]; *P* = 0.021; ES = -0.14) in the control condition compared with baseline. In contrast, jump height significantly improved 30 seconds after the DJ exercise (0.8 cm [0.235, 1.365]; *P* = 0.003; ES = 0.25) compared with baseline. Jump height improved significantly 9 minutes after the SJ with OPL exercise (1.02 cm [0.288, 1.752]; *P* = 0.005; ES = 0.36) compared with the control condition (Table 1).

Significant relationships were detected between the relative back squat 1RM and peak PAPE responses for the DJ (r = 0.63; *P* = 0.003) and SJ with OPL exercises (r = 0.64; *P* = 0.002). No significant relationships were detected between relative back squat 1RM and the time to elicit peak PAPE after any exercises (Figure 3).

A statistically significant interaction effect was detected for peak jump height ($F_{2, 38}$ = 15.657; $P < 0.001$; $\eta^2 = 0.452$). Post hoc analyses revealed a significant improvement in peak jump height in the control condition (0.275 cm [0.061, 0.489]; P = 0.014; ES = 0.10), DJ exercise (1.175 cm [0.851, 1.499]; $P < 0.001$; ES = 0.35), and SJ with OPL exercise (0.875 cm [0.632, 1.118]; $P < 0.001$; ES = 0.26) compared with baseline. In addition, peak jump height improved significantly in the SJ with OPL exercise compared with the control condition (0.865 cm [0.232, 1.498]; P = 0.006; ES = 0.26) (Figure 2).

Table 1. Comparisons of countermovement jump height across all time points within- and between-condition (mean ± SD).

		Time points					Effect Size (Compared with baseline)			
	Condition	Baseline	30 s	3 min	6 min	9 min	30 s	3 min	6 min	9 min
	Control	24.77 ± 2.59	24.55 ± 2.65	24.74 ± 2.91	24.6 ± 2.77	24.42 ± 2.58*	-0.08 (trivial)	-0.01 (trivial)	-0.06 (trivial)	-0.14 (small)
	DJ	24.57 ± 3.13	25.37 ± 3.19*	24.96 ± 3.56	24.84 ± 3.37	24.56 ± 3.3	0.25 (small)	0.12 (small)	0.08 (trivial)	0.00 (trivial)
	OPL	25.04 ± 2.82	24.83 ± 2.92	24.67 ± 2.87	24.75 ± 2.62	25.44 ± 3.09†	-0.07 (trivial)	-0.13 (small)	-0.11 (small)	0.14 (small)
Effect Size	Control vs. DJ		0.28 (small)	0.07 (trivial)	0.08 (trivial)	0.05 (trivial)				
	Control vs. OPL		0.1 (small)	-0.02 (trivial)	0.06 (trivial)	0.36 (moderate)				
	DJ vs. OPL		-0.18 (small)	-0.09 (trivial)	-0.03 (trivial)	0.28 (small)				

DJ: Drop jump; OPL: Optimal power load; *$P < 0.05$: Statistically significant differences compared with baseline; †$P < 0.05$: Statistically significant differences compared with control condition.

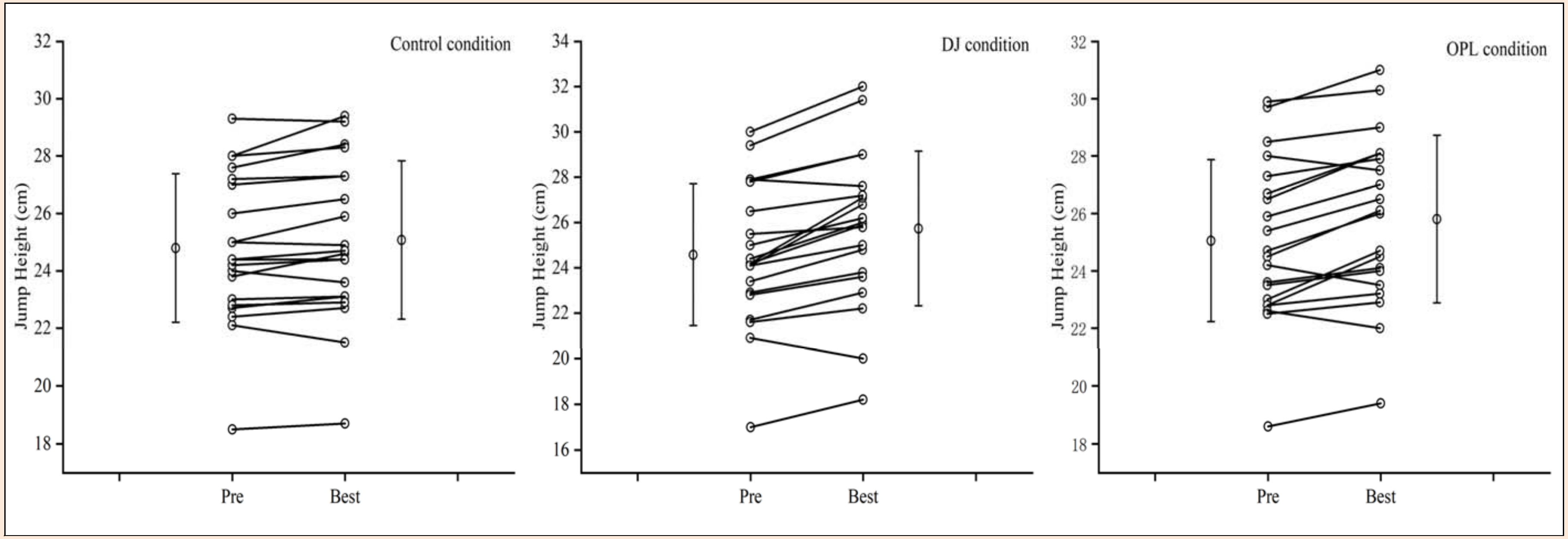

Figure 2. Mean ± SD and interindividual responses in countermovement jump height. OPL = optimal power load; DJ = drop jump.

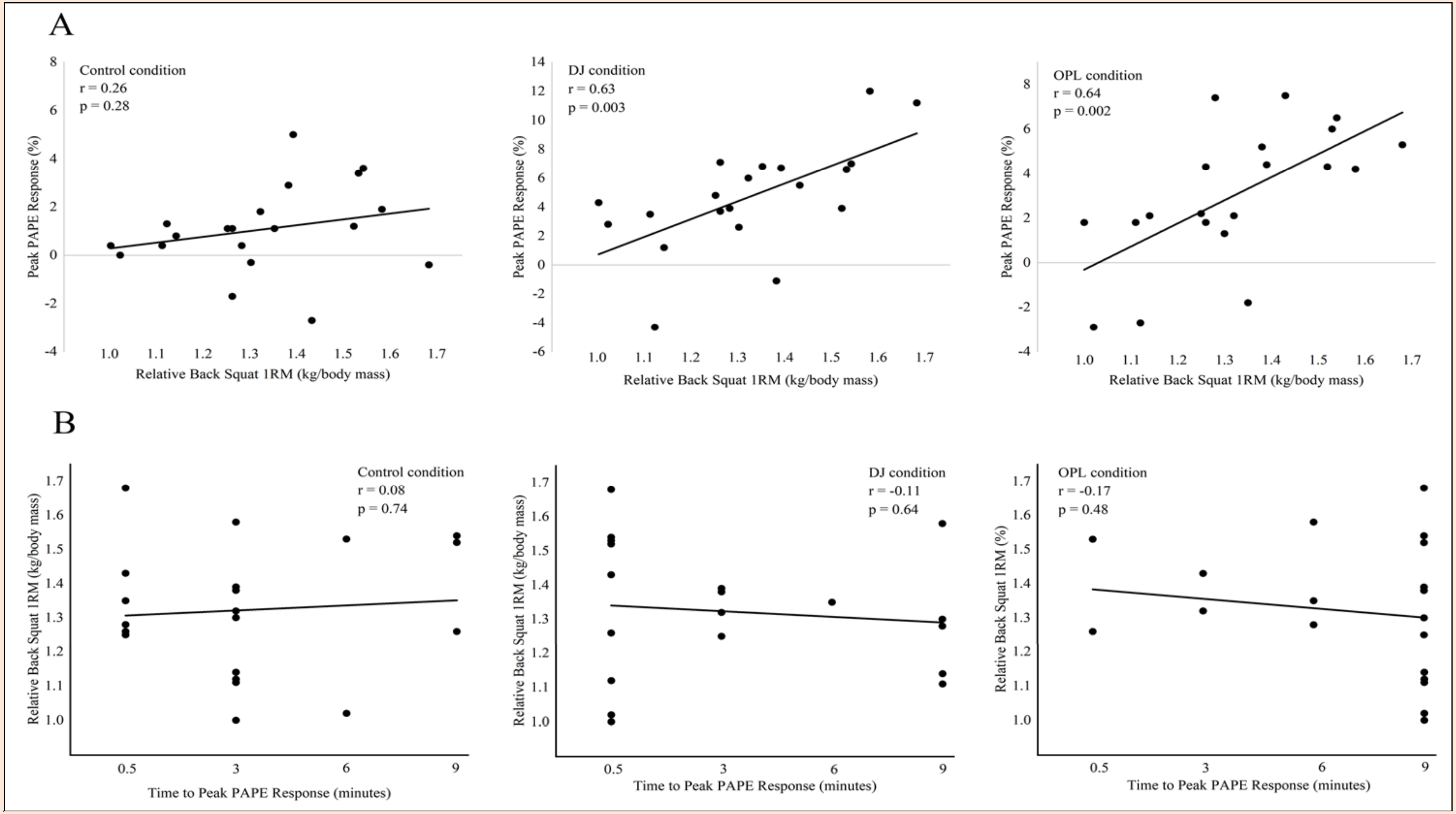

Figure 3. A) Relationships between relative back squat 1RM and peak PAPE responses. B) Relationships between relative back squat 1RM and time to peak PAPE responses. RM = repetition maximum; OPL = optimal power load; DJ = drop jump; PAPE = postactivation performance enhancement.

Discussion

The objectives of this study were to compare the effects of 6 repetitions of DJs with 6 repetitions SJs with OPL on acute CMJ performance and determine whether the PAPE effects are related to strength level in elite RG athletes. In line with our hypothesis, DJ and SJ with OPL exercises led to significant improvements in CMJ height, but the time course and magnitude of PAPE effects varied. Furthermore, RG athletes with a higher relative back squat 1RM, regardless of the exercises used, achieved greater PAPE.

The time course of the PAPE induced by the two exercises were different. Specifically, CMJ height significantly improved 30 seconds after the DJ exercise and 9 minutes after the SJ with OPL exercise. This finding is consistent with a previous meta-analysis (Seitz and Haff, 2016) indicating that PAPE effects are realized earlier after a plyometric exercise (0.3 - 4 minutes) than after a high-intensity exercise (≥5 minutes). Given the relationship between potentiation and fatigue, the use of DJ may produce less fatigue compared to SJ with OPL in RG athletes. DJ is widely recognized as a high-intensity plyometric exercise that primarily recruits type II fibers, which is responsible for PAPE (Boullosa et al., 2020b). However, several studies (de Poli et al., 2020; Zagatto et al., 2022b) showed that DJs did not lead to a change in muscle activity, possibly attributed to the performance assessed. Future studies are needed to confirm the greater recruitment of higher-order motor units during the CMJ assessment. Although no research to date has directly compared the PAPE effects of DJ and SJ with OPL, a recent study (Zagatto et al., 2022a) reported superior sprint performance after 5 DJ repetitions in a cohort of young basketball players, while no PAPE effects were observed following heavy sled towing loaded with 75% body mass. The author attributed the absence of PAPE effects for heavy sled towing to muscle fatigue. In addition, two studies (Dello Iacono et al., 2020a; 2020b) demonstrated a reduction in CMJ and SJ heights 30 seconds after performing SJs with OPL, followed by improvements at post 4 and 8 minutes. These results suggest that fatigue was maximized immediately following the SJ with OPL condition, which partially aligns with our findings. In the current study, SJ may cause more fatigue because a reduction in CMJ height persisted for up to sixth minutes (ES = -0.07 to -0.11). This may be due to the participants' consistent engagement in high-volume RG training, which was not reduced during the experiment, resulting in physical fatigue. This is evidenced by the results of the control condition; a significant decrease in CMJ height relative to the baseline was detected at post 9 minutes. In this context, using DJ may be a more time-efficient training strategy to improve the CMJ performance of elite RG athletes.

CMJ height improved significantly 9 minutes after the SJs with OPL exercise (ES = 0.36, moderate) compared with the control condition. Additionally, CMJ height improved to a greater extent (ES = 0.28, small) after a longer rest interval (9 minutes) following SJ with OPL exercise compared with CMJ height after the DJ exercise, highlighting the effectiveness of SJs with OPL in PAPE in RG athletes. Regarding PAPE research, the high interindividual variability highlights the necessity for individualized approaches (Boullosa et al., 2020b). The OPL approach is determined by individual load-power relationships, allowing each athlete to maximize power output. The SJ is a typical ballistic exercise with accelerated movement throughout the concentric phase. Taken together, the greater mechanical outputs are likely the foundation for the PAPE effects of jump performance. The present study only assessed CMJ height up to 9 minutes following the SJs with OPL. The occurrence and extent of potentiation effects after 9 minutes in RG athletes are unclear. This aspect should be investigated in future studies.

The individual's characteristics, such as strength level, training experience, and sex, impact the PAPE effects (Seitz and Haff, 2016). In the current study, both DJs and SJs with OPL significantly improved CMJ height when the individual peak CMJ performance was analyzed, confirming the interindividual variability in PAPE responses (Figure 2). Furthermore, positive relationships between peak CMJ performance and relative back squat 1RM for both the DJ (r = 0.63) and SJ with OPL (r = 0.64) exercises were detected, indicating that a greater PAPE effect was achieved in athletes with higher strength levels. This results agrees with a previous study (Seitz and Haff, 2016) showing that stronger individuals can achieve greater PAPE effects. However, our results conflict with the study by Boullosa et al. (2020a), who reported improved 1000-m performance after a set of 5 DJs in elite male endurance runners but failed to observe PAPE effects in female athletes. Compared to long-distance runners who may have a greater percentage of slow twitch fibers, RG athletes have powerful muscle groups to achieve good technical performance in competition (Douda et al., 2008); these muscle groups may have a greater percentage of type II muscle fibers. A previous study demonstrated greater potentiation effects in type II muscle fibers in vitro (Hamada et al., 2000). Further research is warranted to compare the impact of different sports on PAPE effects in female athletes.

There are two primary limitations to the current study. The main limitation is the lack of control regarding the participants' regular RG training times during the experiment. All RG athletes were following training programs to prepare for the national championship in May of the following year. Based on the results from the control condition, the lack of recovery before testing led to a reduction in CMJ height. However, this investigation was conducted without interfering with the regular RG-specific training, suggesting that the results of this study apply to real RG training scenarios. Another limitation is the lack of physiological and biomechanical assessments due to logistical constraints. Only the CMJ height was assessed. Therefore, we could not identify the mechanisms for the PAPE effects. Future studies are warranted to measure muscle temperature, muscle activation, and kinetic and kinematic parameters during the CMJ performance to gain a deeper understanding of the PAPE effects.

Conclusion

Coaches can incorporate DJs and SJs with OPL into training (e.g., complex training) or pre-competition warm-up to acutely improve CMJ performance in elite RG athletes. The time to induce PAPE differed between the two exercises. Specifically, DJs immediately improved CMJ performance, while SJs with OPL improved CMJ performance after a longer rest interval. Our results also suggest that RG athletes with higher strength levels will benefit more from these two exercises to improve CMJ height.

Acknowledgements

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Key points

- Drop jumps significantly improved countermovement jump height more rapidly (30 seconds) than squat jumps with optimal power load.
- Squat jumps with optimal power load improved countermovement jump height to a greater extent later (9 minutes) than drop jumps.
- Higher strength level correlated with greater post-activation performance enhancement effects after both drop jumps and squat jumps.

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