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Research article

Acute Effects of Back Squat Combined with Different Elastic Band Resistance on Vertical Jump Performance in Collegiate Basketball Players

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Abstract
The purpose of this study was to compare the acute effects of back squat exercise with or without elastic band on countermovement jump performance. Thirteen collegiate male basketball players (age: 20.5 ± 0.9 years; height: 188.5 ± 8.5 cm; body mass: 82.8 ± 12.9 kg) completed 5 familiarization and 4 experimental sessions separated by at least 48 hours. In the experimental sessions, the order of the conditions was randomized so that the participants performed 1 set of 3 repetitions of barbell back squat at 85% of their one-repetition maximum (1-RM), 1 set of 3 repetitions of back squat at 85% 1-RM with 20% variable resistance training (VRT), 30%VRT, or 40%VRT of the total load coming from the elastic band. Countermovement jump performance was assessed before (baseline), 30 seconds, 3 minutes, 6 minutes, and 9 minutes following each condition. Jump height, rate of force development, peak power, and vastus lateralis, vastus medialis, and medial gastrocnemius electromyography data were collected. Compared with the baseline, 30%VRT significantly improved jump height at 3 minutes post-exercise by 1.3 cm ($P < 0.001$) and 6 minutes post-exercise by 1.2 cm ($P = 0.005$); 40%VRT significantly improved jump height from 30 seconds up to the 9th minute (1.2 to 1.9 cm, $P \leq 0.036$). The superior jump height was also accompanied by improved kinetic and electromyography data. No significant changes were observed in the barbell back squat and 20%VRT conditions. In conclusion, back squat at 85% 1-RM with 40% elastic band resistance led to superior vertical jump performance with an optimal time window of 3 minutes.

Key words: Variable resistance training, post-activation potentiation; power.

Introduction

Resistance training is normally used to improve power performance. According to the strength and power relationship, the power training effects will be limited if the absolute strength of an athlete is low (Cormie et al., 2011). Complex training is a method in which strength and power can be trained simultaneously and has been widely used in team sports (Cormier et al., 2020). The alternation of high-intensity strength exercises and lower-intensity power exercises in a single workout session has been considered both time-efficient and more effective in enhancing power output, e.g., a set of 85% of one-repetition maximum (1-RM) back squat followed by a set of plyometric exercise. Specifically, an intense strength exercise can acutely optimize neuromuscular responses, such as increased myosin light chain phosphorylation, excitability of motoneurons, and recruitment of high-order motor units (Tillin and Bishop, 2009), which are the main factors in improving subsequent power performance. It also leads to increase in muscle temperature and cellular water content (Blazevich and Babault, 2019). Additionally, changes in muscle-tendon stiffness may also contribute to improved power performance (Krzysztofik et al., 2023a), although the evidence remains controversial. This phenomenon is referred to as post-activation potentiation (PAP) (Sale, 2002). The magnitude of PAP is influenced by the net balance of potentiation and fatigue, and power performance increases when the potentiation effects outweigh fatigue at a specific time window.

The time course of PAP responses has been extensively investigated. In a study by Wallace et al. (2019), the twitch and reflex potentiation effects were examined between 20 seconds and 20 minutes following a 10-second maximal plantarflexion isometric contraction. They reported that PAP was significantly greater for the muscle factor at 10 and 30 seconds, and for the neural factor at 4.5 minutes, with a gradual decrease observed over time for both factors. When assessing PAP in terms of athletic performance, meta-analysis has shown that a recovery interval of 3 - 10 minutes (Wilson et al., 2013) or 5 - 7 minutes (Seitz and Haff, 2016a) following a high-intensity (i.e., ≥ 85% 1-RM) strength exercise was more beneficial in inducing PAP compared to intervals of < 2 minutes (Wilson et al., 2013) or 0.3 - 4 minutes (Seitz and Haff, 2016a). Based on the aforementioned results, the optimal recovery interval to induce PAP typically falls within 10 minutes after a high-intensity exercise. In order to maximize training efficiency, it is imperative to explore methods that can rapidly induce PAP. Additionally, a substantial body of literature has demonstrated that optimized PAP is highly individualized (Krzysztofik et al., 2023a, 2023b; Pisz et al., 2023; Spieszny et al., 2022). Therefore, the individual recovery interval between strength and power exercises should also be considered.

Back squat is a commonly utilized exercise to induce PAP because it is biomechanically similar to most lower extremity power performance (Ng et al., 2020). For instance, an improvement in loaded countermovement jump (CMJ) performance was observed following a set of 5-RM back squat (Young et al. 1998). However, it is worth noting that a high-intensity back squat exercise using a bar-

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bell, referred to as constant resistance training (CRT), could result in decreased velocity in the early concentric phase of the movement due to the mechanical disadvantage known as the sticking point (Kompf and Arandjelović, 2017). Additionally, there is a mismatch between the muscle force production ability and the force created by the external load in the remaining concentric phase (Andersen et al., 2022). Theoretically, submaximal muscle activation in the late concentric phase during the CRT may influence the PAP effect (Mina et al., 2019). Alternatively, performing back squat in combination with the elastic band, namely the variable resistance training (VRT), has received more attention in the strength training field (Andersen et al., 2022; McMaster et al., 2009; Shi et al., 2022; Wallace et al., 2006).

The main feature of the VRT is that the load decreases at the bottom and increases at the top throughout the range of motion. In this case, the lower intensity at the bottom can alleviate the influence of the sticking point and facilitate movement acceleration. This is supported by a recent meta-analysis (Shi et al., 2022) which revealed that mean velocity and mean power output during the concentric phase were considerably increased with VRT compared to CRT in an equated load scheme (i.e., lower intensity at bottom and higher intensity at top in the VRT than the CRT). Furthermore, a study (Andersen et al., 2016) demonstrated that overloading (VRT: 113kg vs. CRT: 73kg) in the upper range of motion during the VRT resulted in greater electromyographic (EMG) activity compared to performing CRT. Considering the abovementioned factors, incorporating elastic band into back squat can be an efficient exercise to induce PAP.

Two studies (Seitz et al., 2016b; Strokosch et al., 2018) demonstrated that performing two repetitions of back squat with a barbell loaded to 70% of the 1-RM, supplemented with approximately 14% of the 1-RM from elastic band resistance (where the resistance was the average throughout the range of motion), acutely potentiated horizontal jump performance after 90 seconds of recovery. However, these studies did not include the CRT as a control condition. Another two studies used a similar protocol to compare the acute effects of VRT and CRT on CMJ performance. Mina et al. (2019) reported that one set of three repetitions of VRT (the barbell is loaded to 70% of the 1-RM, with 30% of the 1-RM provided by the elastic band at the top during the back squat) was more effective than CRT (85% 1-RM) in improving CMJ height and peak power output at each post-time point (0.5, 4, 8, and 12 minutes), while Nickerson et al. (2019) did not observe significant differences in CMJ height and peak power output between the two training modalities within 10 minutes post-exercise. It is worth noting that different elastic band resistance can elicit distinct acute neuromuscular responses (Shi et al.,2022), which could be an important factor affecting PAP. Krčmár et al. (2021) compared the acute effects of two elastic band resistance levels (17% 1-RM and 26% 1-RM at the top position) combined with back squat on vertical jump performance. No significant differences in vertical jump height were seen between the two VRT conditions. The authors concluded that greater elastic band resistance induces a greater PAP based on their effect size (ES) data. Meanwhile, the PAP evaluation was only reported at two time points (5 and 10 minutes) in their study, and it remains unclear whether PAP would have been induced earlier by different elastic band resistance levels. Therefore, the purpose of this study was to compare the acute effects of three elastic band resistance combined with back squat and traditional barbell back squat conditions on CMJ performance in collegiate male basketball players. We hypothesize that the greater the elastic band resistance is, the higher the PAP will be.

Methods

Study Design

A randomized, counter-balanced, cross-over design was used to compare the effects of back squat combined with 20% elastic band resistance (20%VRT), 30% elastic band resistance (30%VRT), 40% elastic band resistance (40%VRT), and traditional barbell back squat (CRT) on subsequent CMJ performance. The selection of the three elastic band resistance was based on the finding that 10% elastic band resistance had no effect on EMG (Ebben and Jensen, 2002), and previous research has commonly used this range of resistance (Krčmár et al., 2021; Mina et al., 2016, 2019; Nickerson et al., 2019). Participants visited the laboratory nine times, consisting of 5 familiarization and 4 experimental sessions separated by at least 48 hours (Peng et al., 2021). During the first three visits, participants were familiarized with the VRT and the testing procedures. During the fourth and fifth visits, their 3-RM back squat and elastic band resistance levels were measured. Subsequently, the 4 PAP conditions were randomly performed in separate experimental sessions, including a standardized warm-up, baseline CMJ test, either a VRT or CRT PAP condition, and the CMJ test after 30 seconds, 3 minutes, 6 minutes, 9 minutes of recovery (see Figure 1). The post-time points were determined based on previous research (Seitz and Haff, 2016a). Due to high interindividual variability in PAP responses, the optimal CMJ performance of each individual was further examined after each condition. Jump height, rate of force development (RFD), peak power output, vastus lateralis (VL), vastus medialis (VM), and medial gastrocnemius (MG) EMG during the eccentric and concentric phases were measured during all CMJ test.

Subjects

Thirteen collegiate male basketball players (3 guards, 8 forwards, and 2 centers) with at least a certified national II level performance of basketball and five years of experience in basketball training (age: 20.5 ± 0.9 years; height: 188.5 ± 8.5 cm; body mass: 82.8 ± 12.9 kg; back squat 1-RM relative to body mass: 1.4 ± 0.3) volunteered to participate in the study, expect for one subject who did not complete the study. A priori sample size calculation indicated that 12 participants were sufficient to achieve 90% statistical power, with an alpha error of 0.05, and ES of 0.4. All participants were actively engaged in basketball training and competition, and had no recent illness or lower-limb injury. They were instructed to avoid strenuous exercise for at least 24 hours before testing. Most of them had previous experience with recreational resistance training (upper and

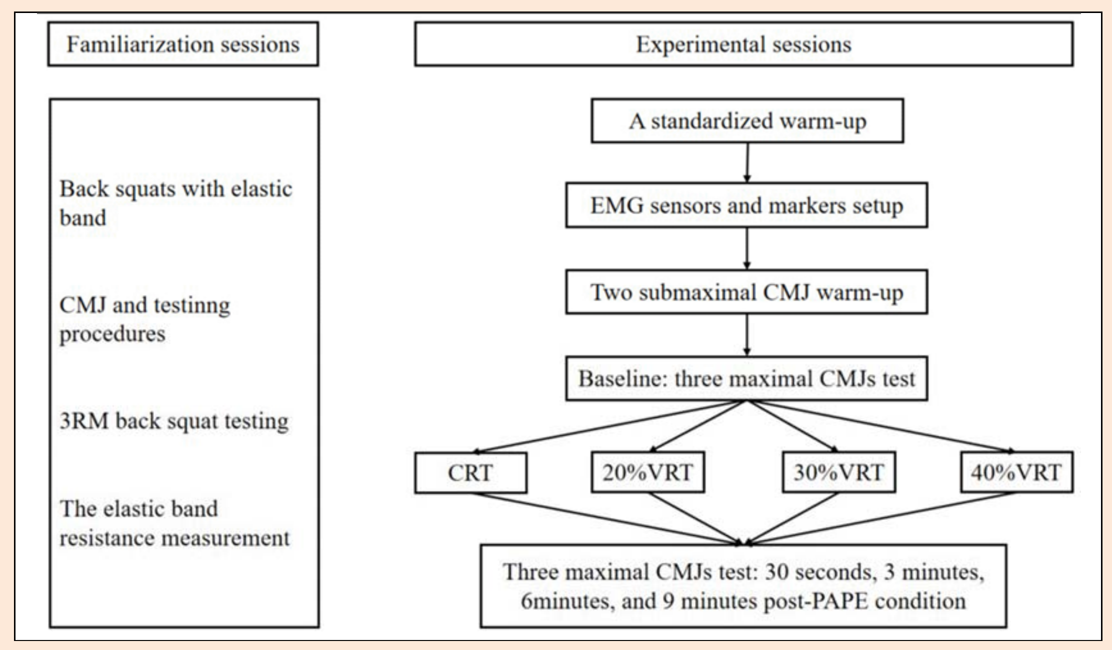

Figure1. Schematic of the study design. RM = repetition maximum; CMJ = countermovement jump.

lower body resistance training at least 2 days per week) for 6 months before the study. Written informed consent was signed after explaining the potential benefits and risks of the study. The study was approved by the Shanghai University of Sport Science Research Ethics Committee.

Procedures

Familiarization sessions

Prior to the experimental sessions, five familiarization sessions were conducted over a period of 3 weeks. Since none of the participants had prior training experience of the VRT, they performed back squat combined with elastic band to ensure adequate familiarization with VRT during the first three sessions. In session 3, the participants also practiced the CMJ and familiarized themselves with the testing procedures. Afterward, the 3-RM back squat testing was conducted for each player, followed by the calculation of the 1-RM value using the formula outlined in the NSCA guidelines (Haff and Triplett, 2016). This approach has been demonstrated to be valid (Chaouachi et al., 2011). Firstly, participants completed a standardized warm-up consisting of 5 minutes of low-intensity running, followed by 10 minutes of dynamic stretching exercises (e.g., waking knee lift and forward lung with elbow to instep). Then, participants performed 7 - 10, 5 - 7, and 3 - 5 repetitions at 50%, 70%, and 80% of their estimated 1-RM, respectively. After the final warm-up set, participants performed 3 to 4 trials at their estimated 3-RM. Two minutes of rest was provided for the warm-up sets, whereas 4 minutes of rest was taken between the remaining trials. The eccentric and concentric phases of the back squat were executed with a self-regulated tempo following the methodology established in previous research (Wilk et al., 2020a, 2020b). Participants were instructed to position their feet shoulder-width apart, with toes pointing forward or slightly outward, and to squat until their knees reached a 90° angle (thigh relative to the shank). Participants received strong verbal encouragement to give their maximal effort.

In the last familiarization session, the elastic band (Rising, Nantong, China) resistance was measured based on the method used in previous studies (Krčmár et al., 2021; Mina et al., 2019). Briefly, the elastic band resistance levels in the fully extended and flexed position of the back squat were recorded when the participant stood on a force plate, which measures the vertical ground reaction forces (GRF) (Kistler, model 9290AA, Winterthur, Switzerland). The target resistance was obtained through a trial-and-error method by changing the color and number of elastic bands. The actual elastic band resistance for 20%VRT, 30%VRT, and 40%VRT ranged from 1.4% 1-RM (1.7 kg) to 17.4% 1-RM (19.9 kg), 2.7% 1-RM (3 kg) to 24.8% 1-RM (28.7 kg), and 2.8% 1-RM (3.1 kg) to 33.8% 1-RM (39.2 kg) at the bottom and top positions of the back squat, respectively.

Post-activation Potentiation Protocols

The PAP conditions consisted of 20%VRT, 30%VRT, 40%VRT, and CRT, where participants performed 1 set of 3 repetitions of back squats at 85% 1-RM (CRT condition). For all the VRT conditions, half of the elastic band resistance was removed from the barbell to ensure that the work throughout the range of motion between VRT and CRT was equivalent (Mina et al., 2019). For instance, if the barbell was loaded with 100 kg in the CRT condition, the total load in the 40%VRT condition at the top position of the back squat would be 120 kg, with 40 kg coming from elastic band resistance. Therefore, to equate the work of 100 kg, the total load in the 40%VRT condition at the bottom position was approximately 80 kg, with only the barbell provided the load. Participants completed a standardized warm-up as they did in the 3-RM testing session. After 2 minutes of baseline CMJ assessment, participants performed the back squat exercise according to their allocated condition. They were instructed to bend their knees in a self-paced but controlled manner, with the upper leg being parallel to the ground, and to complete the concentric phase as fast and forcefully as possible.

Countermovement jump assessment

Participants performed two submaximal CMJs at 50% and 80% of their perceived maximal effort. One minute later, 3 baseline CMJs were performed with a 15-second rest interval between trials. After the back squat exercise, 3 maximal CMJs were repeated at each post-time point. Researchers provided verbal encouragement throughout the testing. The best jump height was used for the analysis. During the CMJ, participants started from a standing position with fully extended knees and hands on their hips. They then executed a rapid downward movement to a self-selected height followed by a forceful vertical jump.

Electromyography data collection and analyses

Surface EMG signals were collected using the Ultium-EMG sensor system (Noraxon Inc, Scottsdale, AZ, USA) with a sampling frequency of 2000 Hz. The EMG signals were synchronized with the GRF and kinematic data using Qualisys Track Manager software (Qualysis Oqus 400, Gothenburg, Sweden). After the standardized warm-up, participants' skin was shaved, abraded, and cleaned with alcohol to reduce skin impedance. The EMG electrodes were AgCl with an interelectrode distance of 2 cm and were placed over the muscles in the direction of the underlying muscle fibers on the dominant leg (i.e., the one used to kill the ball). According to SENIAM recommendations (www.seniam.org), the electrode for the VL was placed at two-thirds on the line from the anterior spina iliac superior to the lateral side of the patella, the electrode for the VM was placed at four-fifths on the line between the anterior spina iliac superior and the joint space in the front of the anterior border of the medial ligament, and the electrode for the MG was placed on the most prominent bulge of the muscle.

The raw EMG data were processed using a custom script written in MATLAB software (MATLAB, version R2020b, MathWorks Inc., Natick, USA). The data were full-wave rectified, filtered using a 10 - 400 Hz bandpass (fourth-order Butterworth filter), and converted to root mean square (RMS) with a 50-ms sampling window. To normalize the RMS values, the participant's peak RMS value during the first repetition of the back squat was used for standardization (Nijem et al., 2016). Normalized mean RMS data were calculated for the eccentric and concentric phases during CMJ, respectively.

Kinetic and kinematic data collection and analyses

A Kistler force plate with a sampling frequency of 1000 Hz and 8-camera Qualisys motion capture system (Qualisys, Gothenburg, Sweden) with a sampling frequency of 200 Hz were synchronized to collect the GRF and kinematic data during the CMJ. Fourteen reflective markers (diameter 14mm) were placed on the pelvis and the dominant leg. Five markers were placed on the pelvis (left and right anterior superior iliac spine, iliac crest, and L5 spinous process), while the remaining markers were placed on the greater trochanter, medial and lateral epicondyles, medial and lateral malleoli, first and fifth metatarsal heads, toe, and heel. The data were processed in Qualisys Track Manager and then transferred to Visual 3D software (C-motion Inc, Germantown, USA) for segment modeling and analysis. The pelvis was modeled as a conical frustum, and the center of mass (COM) was estimated based on segment geometry (Chiu and Salem, 2010). Maker coordinates and GRF data for the CMJ were smoothed with a Butterworth fourth-order filter at a cutoff frequency of 10 Hz (Lam et al., 2021) and 50 Hz (Nibali et al., 2015), respectively.

The GRF and COM velocity data were used to identify the eccentric and concentric phases of the CMJ. The start of the eccentric phase was defined as the point when GRF data fell below a threshold value of 2.5% relative to the participants' body mass (Meylan et al., 2011). The end of the eccentric phase was defined as the point when the velocity of COM reached zero. The start of the concentric phase was defined as the time at which the COM velocity became positive. And the end of the concentric phase was defined as the instant when the GRF data fell below a threshold value of 20 N (Harry et al., 2020). Jump height was determined by subtracting the height of the L5 spinous process marker during standing from the maximum height achieved during the CMJ (Lam et al., 2021). RFD was determined between the minimum and maximum force during the eccentric phase (Cormie et al., 2010). Peak power was calculated as the product of the peak COM velocity and peak GRF data during the concentric phase. Both RFD and peak power data normalized to body mass.

Statistical analyses

Descriptive statistics were presented as mean ± SD. Statistical Software (version 25.0. SPSS Inc., Chicago, IL, USA) was used to analyze the data. Normality was checked using the Shapiro-Wilk test, all data showed a normal distribution. Reliability for all outcomes were determined during the baseline CMJ across conditions. Moderate to high intraclass correlation coefficient (ICC) were calculated for jump height (0.89), RFD (0.62), and peak power (0.9). ICC values for RMS data ranged from 0.6 to 0.75, 0.6 to 0.65, 0.64 to 0.8 for VL, VM, and MG, respectively. A 2-way repeated-measures analysis of variance (ANOVA) (4 conditions × 5 time points) was used to examine each dependent variable. A second 2-way ANOVA was performed to investigate the differences in CMJ height, peak power, and RFD between baseline and individual peak PAP responses. In case of violation of sphericity occurred, the Greenhouse-Geisser correction was used to adjust degrees of freedom. If significant interaction or main effect was detected, post hoc pairwise comparisons were conducted using Bonferroni adjustment. The 95% confidence interval (CI) was used to estimate the range of mean differences. ES were calculated to determine the magnitude of PAP using Cohen's *d*, where 0.2, 0.5, and 0.8 were considered small, moderate, and large, respectively (Cohen, 1988). The alpha level was set at $P < 0.05$.

Results

No statistically significant interaction effects were found for jump height (F = 1.69, P = 0.145), peak power (F =

0.82, P = 0.553), and RFD (F = 1.56, P = 0.189). A statistically significant main effect for time was observed for jump height (F = 7.77, P < 0.001), peak power (F = 5.48, P = 0.001), and RFD (F = 4.5, P = 0.004). Post hoc analyses revealed that 30%VRT significantly improved jump height and peak power at post 3 minutes (height: + 1.3 cm [0.8, 1.7], P < 0.001; peak power: +1.65 w/kg [0.53, 2.76], P = 0.003) and 6 minutes (height: + 1.2 cm [0.3, 2], P = 0.005; peak power: +1.95 w/kg [0.3, 3.86], P = 0.045), as well as RFD at post 30 seconds (+ 6.04 N/s·kg [1.32, 10.76], P = 0.003) and 3 minutes (+ 6.94 N/s·kg [3.82, 10.05], P < 0.001) compared with baseline. Similarly, 40%VRT significantly improved jump height at post 30 seconds (+ 1.4 cm [0.6, 2.1], P < 0.001), 3 minutes (+ 1.9 cm [0.9, 2.9], P < 0.001), 6 minutes (+ 1.9 cm [0.5, 3.2], P = 0.006), and 9 minutes (+ 1.2 cm [0.1, 2.4], P = 0.036), as well as RFD at post 3 minutes (+ 8.94 N/s·kg [0, 17.89], P = 0.05) compared with baseline. In contrast, no statistical significance was found for these outcomes across all time points in the CRT and 20% VRT conditions. The data are presented in Table 1.

The distribution of time points for the individual peak PAP responses in CMJ height, peak power, and RFD are shown in Table 2. A statistically significant interaction effect was found for jump height (F = 3.26, P = 0.03), but not for peak power (F = 2.64, P = 0.06) and RFD (F = 0.84, P = 0.48). However, there was a statistically significant main effect of time for peak power (F = 101.76, P < 0.001) and RFD (F = 80.93, P < 0.001). Post hoc analyses revealed that jump height, peak power, and RFD significantly improved from baseline to the peak time point in all conditions ($P \leq 0.001$).

Normalized mean RMS data of VM, VL, and MG in all time points are reported in Table 3. No statistically significant interaction effects were found for VM (F = 0.3, P = 0.989; eccentric phase and F = 0.79, P = 0.656; concentric phase), VL (F = 1.54, P = 0.191; eccentric phase and F = 0.84, P = 0.529; concentric phase), and MG (F = 1.48, P = 0.14; eccentric phase and F = 0.68, P = 0.772; concentric phase). However, a statistically significant main effect for time in the concentric phase was observed for VM (F = 6.4, P < 0.001) and VL (F = 4.75, P = 0.003). Post hoc analyses revealed that 30%VRT significantly improved VM RMS at post 3 minutes compared to post 6 minutes (+ 7.8 % [2.5, 13.1], P = 0.003) and 9 minutes (+ 11.2 % [1.7, 20.8], P = 0.017), VL RMS at post 3 minutes compared to baseline (+ 6.7 % [1.6, 11.9], P = 0.008) and post 9 minutes (+ 8.4 % [1.6, 15.1], P = 0.012), VL RMS at post 6 minutes (+ 6.3 % [0.6, 12], P = 0.026) compared to post 9 minutes. In addition, 40%VRT significantly improved VL RMS at post 3 minutes (+ 9.9 % [0.7, 19.1], P = 0.03) and 6 minutes (+ 7 % [0.1, 13], P = 0.018) compared to baseline. In contrast, no interaction and main effect were observed for MG RMS.

Table2. **The distribution of time points for individual peak PAP response in different conditions.**

	Post 30 seconds	Post 3 minutes	Post 6 minutes	Post 9 minutes
CRT_height	4	4	4	1
20%VRT_height	4	3	3	3
30%VRT_height	3	4	4	2
40%VRT_height	1	6	5	1
CRT_power	6	2	2	3
20%VRT_power	3	5	3	2
30%VRT_power	2	3	5	3
40%VRT_power	3	4	5	1
CRT_RFD	5	4	2	2
20%VRT_RFD	4	3	2	4
30%VRT_RFD	5	4	1	3
40%VRT_RFD	2	3	4	4

CRT, constant resistance training; VRT, variable resistance training; RFD, rate of force development.

Discussion

The purpose of this study was to compare the acute effects of back squat combined with different elastic band resistance and traditional barbell back squat on CMJ performance. Aligned with our hypothesis, the results revealed that performing back squat combined with greater elastic band resistance (i.e., 30%VRT and 40%VRT) significantly improved CMJ height at an earlier time point and to a greater extent, especially in the 40%VRT condition.

Table1. **The height, peak power, and RFD of the countermovement jump performance across all time points (mean ± SD).**

	Baseline	Post 30 seconds	ES	Post 3 minutes	ES	Post 6 minutes	ES	Post 9 minutes	ES
Height (cm)									
CRT	51.7±4.96	51.99±4.74	0.06	52.15±4.95	0.09	52±4.53	0.06	51.25±4.44	−0.1
20%VRT	51.95±4.26	52.09±4.18	0.03	52.25±4.92	0.07	52.39±5.31	0.09	52.16±4.83	0.05
30%VRT	51.71±4.59	52.77±4.93	0.22	53±4.66*	0.28	52.87±4.92*	0.24	52.43±4.85	0.15
40%VRT	52.02±4.69	53.39±4.53*	0.3	53.91±4.73*	0.4	53.87±5.16*	0.38	53.25±4.52*	0.27
Peak power (w/kg)									
CRT	52.06±5.46	52.64±5.53	0.11	52.63±5.64	0.1	52.09±4.81	0.01	51.85±4.68	−0.04
20%VRT	52.53±4.75	52.63±4.17	0.02	53.25±5.03	0.15	53.2±5.5	0.13	52.48±5.21	−0.01
30%VRT	52.06±4.96	52.93±5.79	0.16	53.7±4.89*	0.33	54±5.53*	0.37	52.67±5.28	0.12
40%VRT	52.6±4.85	53.91±4.67	0.28	54.43±5.55	0.35	54.17±5.55	0.3	52.92±5.65	0.06
RFD (N/s·kg)									
CRT	68.58±11.06	67.43±14.32	−0.09	68.62±15.59	0	65.2±18.6	−0.22	66.38±14.37	−0.17
20%VRT	66.8±13.37	70.01±13.63	0.24	70.76±16.43	0.26	70.39±15.63	0.25	70.12±14.92	0.23
30%VRT	68.49±15.13	74.53±15.15*	0.4	75.43±16.32*	0.44	71.21±14.71	0.18	70.07±16.22	0.1
40%VRT	65.18±14.11	67.34±14.62	0.15	74.12±18.58*	0.54	73.72±19.31	0.5	70.44±17.88	0.33

CRT, constant resistance training; VRT, variable resistance training; RFD, rate of force development; ES, effect size. *$P \leq 0.05$: Statistically significant differences compared with baseline.

Table3. Normalized mean RMS (%) of the countermovement jump performance across all time (mean ± SD).

	Phase	Baseline	Post 30 seconds	ES	Post 3 minutes	ES	Post 6 minutes	ES	Post 9 minutes	ES
					VM					
CRT	ECC	32.96 ± 10.1	31.12 ± 10.92	−0.17	32.35 ± 9.01	−0.06	30.94 ± 13.64	−0.17	31.95 ± 9.26	−0.1
	CON	75.54 ± 20.92	78.8 ± 23.26	0.15	78.43 ± 18.05	0.15	72.14 ± 19.32	−0.17	71.9 ± 20.49	−0.18
20%VRT	ECC	35.75 ± 8.03	35.13 ± 11.19	−0.06	36.31 ± 9.45	0.06	35.54 ± 10.83	−0.02	37.43 ± 16	0.13
	CON	83.68 ± 30.32	81.91 ± 2.5	−0.08	79.7 ± 25.26	−0.14	79.49 ± 22.97	−0.16	79.8 ± 18.84	−0.15
30%VRT	ECC	33.86 ± 6.98	34.6 ± 8.77	0.09	32.22 ± 6.57	−0.24	32.31 ± 8.14	−0.2	34.2 ± 7.35	0.05
	CON	69.25 ± 11.11	75.41 ± 13.77	0.49	76.42 ± 14.34†‡	0.56	68.62 ± 13.37	−0.05	65.18 ± 20.15	−0.25
40%VRT	ECC	29.69 ± 13.48	30.35 ± 12.52	0.05	29.81 ± 12.3	0.01	28.88 ± 10.66	−0.07	28.77 ± 11.56	−0.15
	CON	64.93 ± 26.05	69.29 ± 22.37	0.18	69.3 ± 20.88	0.19	66.39 ± 20.83	0.06	61.73 ± 23.38	−0.15
					VL					
CRT	ECC	36.67 ± 18.49	37.5 ± 23.1	0.04	40.12 ± 24.93	0.16	33.12 ± 15.31	−0.21	34.87 ± 18.69	−0.1
	CON	57.24 ± 12.25	55.98 ± 14.26	−0.09	59.65 ± 17.49	0.16	54.71 ± 16.97	−0.17	56.75 ± 21.18	−0.03
20%VRT	ECC	31.6 ± 8.59	30 ± 9.68	−0.17	29.41 ± 8.16	−0.26	32 ± 9.68	0.04	30.83 ± 11.28	−0.08
	CON	66.3 ± 16.08	68.87 ± 17.37	0.15	70.6 ± 21.4	0.23	67.5 ± 19.45	0.07	64.98 ± 19.13	−0.07
30%VRT	ECC	36.8 ± 20.8	34.46 ± 16.32	−0.13	31.12 ± 18.26	−0.29	35.09 ± 23	−0.08	34.96 ± 21.98	−0.09
	CON	63.86 ± 20.08	67.76 ± 19.2	0.2	70.59 ± 20.83*‡	0.33	68.5 ± 18.48‡	0.24	62.22 ± 20.3	−0.08
40%VRT	ECC	31.62 ± 7.25	35.37 ± 12.43	0.37	30.79 ± 9.01	−0.1	31.88 ± 9.73	0.03	31.97 ± 10.93	0.04
	CON	57.08 ± 24.64	63.58 ± 26.31	0.26	66.99 ± 27.39*	0.38	64.08 ± 25.33*	0.28	58.8 ± 24.85	0.07
					MG					
CRT	ECC	21.14 ± 8.3	20.16 ± 9.8	0.2	23.17 ± 11.96	0.2	22.39 ± 12.15	0.12	18.51 ± 7.36	−0.34
	CON	80.57 ± 24.95	81.75 ± 23.34	0.05	80.93 ± 27.54	0.01	79.6 ± 20.45	−0.04	78.04 ± 23.06	−0.11
20%VRT	ECC	22.22 ± 12.23	22.93 ± 13.84	0.05	22.57 ± 11.66	0.03	20.91 ± 11.64	−0.11	21.7 ± 11.6	−0.04
	CON	88.1 ± 29.5	85.63 ± 28.01	−0.09	85.88 ± 28	−0.08	90.37 ± 31.45	0.07	84.27 ± 28.93	−0.13
30%VRT	ECC	21.12 ± 13.16	19.54 ± 7.63	−0.15	19.4 ± 13.14	−0.13	23.98 ± 16.25	0.19	24.4 ± 16.92	0.22
	CON	89.75 ± 40.97	98.25 ± 52.1	0.18	90.11 ± 35.52	0.01	90.1 ± 34.04	0.01	85.91 ± 35.17	−0.1
40%VRT	ECC	26.81 ± 15.67	22.63 ± 13.95	−0.28	21.91 ± 13.24	−0.34	24.03 ± 14.96	−0.18	21.8 ± 13.2	−0.35
	CON	90.92 ± 33.22	90.53 ± 31.32	−0.01	94.33 ± 29.28	0.11	89.3 ± 32.92	−0.05	86.71 ± 33.25	−0.13

CRT, constant resistance training; VRT, variable resistance training; VM, vastus medialis; VL, vastus lateralis, MG, medial gastrocnemius; ECC, eccentric; CON, concentric; ES, effect size. $^{*}P \le 0.05$: Statistically significant differences compared with baseline; †$P < 0.5$, Statistically significant differences compared with post 6 minutes; ‡$P < 0.5$, Statistically significant differences compared with post 9 minutes.

The improvements in CMJ performance were accompanied by enhancements in RFD, peak power output, and extensor RMS during CMJ. In addition, both the CRT and 20%VRT conditions also showed the potential to improve CMJ performance at different post-time points when analyzing individual peak performance.

The main finding of this study was that the 40%VRT optimized the PAP effects, which was demonstrated by a significant improvement in CMJ height as early as post 30 seconds (1.4 cm, ES = 0.3) compared to baseline, and the PAP lasted until the 9th minute (1.2 - 1.9 cm, ES = 0.27 - 0.4). Moreover, the 30%VRT resulted in a significant improvement in CMJ height at both post 3 minutes (1.3 cm, ES = 0.28) and 6 minutes (1.2 cm, ES = 0.24), with a small ES (0.22) observed at post 30 seconds. In contrast, no significant changes in CMJ height were observed at any of the post-tests in either the CRT or 20%VRT conditions. Young et al. (1998) were the first to investigate the effects of traditional back squat (i.e., CRT) on CMJ performance and observed a 2.8% improvement in CMJ height after performing 5-RM back squat with a recovery interval of 4 minutes. Our study found that both the CRT and 20%VRT conditions elicited PAP when analyzing individual peak performance time points. This highlights the importance of assessing an individual's recovery time to maximize PAP, regardless of whether CRT or VRT is utilized.

As far as we are aware, only one study (Krčmár et al., 2021) compared the acute effects of different elastic band resistance combined with back squat on vertical jump performance. Their results showed that 30%VRT seems to be a better stimulator to induce PAP in all post-tests when compared with the 20%VRT after three sets of four repetitions of back squats at 85% 1-RM in a cohort of resistance-trained female athletes. However, they only evaluated PAP at the 5th and 10th minutes after the last set of back squats. In the current study, we chose multiple time points to fully evaluate the temporal profile of PAP, and our results indicate that utilizing greater elastic band resistance can elicit PAP at earlier time points.

Consistent with our study, Mina et al. (2019) reported that 35%VRT led to superior CMJ performance at post 30 seconds, 4, 8, and 12 minutes compared to baseline and the CRT condition in a group of resistance-trained men. It is noteworthy that all the aforementioned studies used an equated load scheme when designing the VRT, which is a more suitable methodology to increase mean velocity and power while performing the VRT (Shi et al., 2022). The biomechanical similarity between the VRT and the subsequent powerful performance likely plays an important role in optimizing PAP. Specifically, when using greater elastic band resistance in the equated load scheme, the load that an individual lifts will decrease in the early concentric phase (i.e., sticking point), which seems to be effective in increasing the concentric velocity. Additionally, the load will be increased to a greater degree in the upper range of motion (i.e., a more mechanical advantage), this feature has been demonstrated to be in favor of increasing muscle activation (Andersen et al., 2016), which is proposed as one of the underpinning mechanism of PAP

(Tillin and Bishop, 2009). Moreover, greater elastic band resistance at the top position of the back squat appears to have a positive impact on increasing eccentric velocity, potentially leading to greater stretch-shorten cycle (SSC) and terminal eccentric forces (Wallace et al., 2018). Therefore, alterations in kinetics and kinematics during the eccentric phase of the VRT cannot be ruled out as a contributing factor to the PAP.

Several factors, in addition to the strength exercise and recovery time, can affect the effectiveness of PAP, such as individual's relative strength level. Seitz et al. (2016b) reported that stronger individuals and those with more resistance training experience could exhibit greater PAP. In the current study, most of the participants were recreationally resistance-trained. Our results showed that CRT did not significantly potentiate CMJ performance when each post time point was analyzed, which is similar to previous studies involving participants with less resistance training experiences (Khamoui et al., 2009; Scott et al., 2017; Timon et al., 2019). In contrast, both 30%VRT and 40% VRT can effectively induce PAP, indicating that the VRT is a viable exercise not only for experienced (Krčmár et al., 2021; Mina et al., 2019) but for less experienced athletes. In addition, considering the positive correlation between individual's strength level and PAP when utilizing CRT (Kilduff et al., 2008), further investigation is required to determine whether VRT can elicit greater PAP in stronger individuals. Although the participants in this study had a lower strength level, with a mean relative back squat 1-RM was 1.4 times their body mass, they exhibited a high-level power ability based on baseline data (i.e., jump height was about 52 cm), which may account for the small ES obtained in the 30%VRT and 40%VRT conditions. Similarly, Nickerson and colleagues (2019) reported a trivial to small ES for CMJ height at all post-tests following a set of three repetitions of back squat at 71% 1-RM combined with 27% 1-RM elastic band resistance. However, the lack of statistical significance when compared to baseline may also be attributed to the participants' high levels of power in CMJ performance (i.e., jump height was about 56 cm in baseline).

The neuromuscular optimizations (i.e., RFD, peak power, and EMG) during the CMJ at post-tests provided further confirmation of the enhancements of CMJ height in the 30%VRT and 40% VRT conditions, which align with some previous studies (Mina et al., 2019; Nickerson et al., 2019; Scott et al., 2018). CMJ is a classic SSC exercise, which combines eccentric and concentric muscle actions. A previous study demonstrated that changes in neuromuscular responses during the eccentric phase contribute to improvement in concentric muscle performance (Cormie et al., 2010). Several mechanisms have been proposed to underpin this phenomenon including, but not limited to, the storage and release of elastic energy in the tendon (Kubo et al., 1999), the generation of greater force from stretch reflexes (Bobbert et al., 1996), and the augmentation of contractile elements (Cormie et al., 2010). The present study showed that eccentric RFD significantly improved at post 30 seconds (ES = 0.4) and 6 minutes (ES = 0.44) in the 30%VRT condition and post 3 minutes (ES = 0.54) in the 40%VRT condition compared to baseline. The timing of the improvement in RFD in the present study partly aligns with that reported by Wallace et al. (2019), who found significantly greater RFD at 10 and 30 seconds (twitch potentiation) after a 10 seconds plantarflexion maximum isometric contraction, as well as at 4.5 minutes (Hoffmann reflex potentiation). An increased magnitude of RFD indicated that individuals were able to generate greater vertical GRF in a shorter period of time during the eccentric phase, which may positively enhance SSC mechanics. As a consequence of the improvement of eccentric force, participants were able to increase their concentric performance. This is further supported by our results that the peak power output was significantly increased at post 3 (ES = 0.33) and 6 (ES = 0.37) minutes in the 30%VRT condition, with small to moderate ES (0.28 - 0.35) observed but no statistically significant differences at post 30 seconds, 3 and 6 minutes were observed in the 40%VRT condition. In addition, although the CRT and 20%VRT conditions did not have significant effects on RFD and peak power output at each time point, significant improvements were observed at individualized peak performance time points.

Meanwhile, the concentric RMS amplitudes in the 30%VRT and 40%VRT conditions at selected post time points were also greater than baseline for VM and VL (Table 3), highlighting the occurrence of PAP. The increased VL RMS amplitude is consistent with a previous study where the concentric VL EMG data for CMJ significantly increased from post 30 seconds up to the 12th minute compared to the pre-test after the 35%VRT condition (Mina et al., 2019). This suggests that the increased elastic band resistance may result in higher-order motor unit recruitment (Andersen et al., 2016), potentially enhancing the transmission of action potentials at the spinal cord. Collectively, the improvements of biomechanical variables (i.e., RFD, peak power, and RMS amplitude) have contributed to the CMJ height enhancement.

This study has some limitations that need to be acknowledged. The participants had a recreational resistance training experience; however, their power was high based on the baseline data (CMJ height was about 52 cm). Nevertheless, the current PAP protocols may also be applicable to the athletes who are well resistance-trained, as stronger athletes tend to induce PAP to a greater extent than weaker athletes (Seitz and Haff, 2016a). Future research is needed to explore this conjecture. Furthermore, a limitation of the current study was the use of a self-controlled manner in the eccentric phase during the back squat, which may attenuate the effects of the larger elastic band tensions on possibly increased eccentric velocity. This, in turn, may further affect the PAP effects.

Conclusion

Back squat at 85% 1-RM combined with 30% and 40% elastic band resistance were effective exercises to generate PAP in a group of recreationally resistance-trained basketball players. The 40% elastic band resistance was more suitable to induce PAP, where CMJ height was enhanced with an optimal time window of 3 minutes (half of the participants reached peak CMJ performance). This effect is likely attributable to the improved neuromuscular responses during CMJ. Furthermore, it is crucial to identify an individual's optimal performance time to maximize the benefits of PAP.

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Key points

- Countermovement jump performance increased following a set of three repetitions of back squat at 85% 1-RM with 30% and 40% of the total load from elastic band.
- Performing the back squat at 85% 1-RM with 40% elastic band resistance led to superior jump performance with an optimal time point of 3 minutes.
- When analyzing individual peak performance time points, a significant improvement in countermovement jump was observed following the implementation of the traditional barbell back squat and back squat with 20% elastic band resistance.

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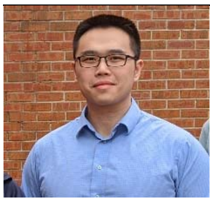

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