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RESEARCH

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Effects of overcoming isometric unilateral conditioning activity on subsequent single-leg drop jump in elite and amateur volleyball players: a randomized crossover trial

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Abstract

Background The study aimed to assess the acute effects of overcoming isometric split squats on subsequent single-leg drop jump (DJ) performance and the contralateral effect in volleyball players, considering training status differences.

Methods Ten male elite (ELI) and ten amateur (AMA) volleyball players took part in two experimental sessions in which they performed conditioning activity (CA) consisted of 3 sets of overcoming isometric 3-second split squats, differing in the limb used: dominant (DL) or non-dominant (ND-L). Single-leg DJ was performed before and at the 4th and 8th minute post-CA for both limbs. The best post-CA attempt in terms of jump height (JH) was analyzed.

Results Results revealed a significant increase in jump height (JH) in the non-dominant limb (ND-L) from 13.7 ± 2.6 cm to 15.5 ± 2.7 cm after CA performed by the ND-L ($p = 0.001$; Hedge's g = 0.65). Similarly, the reactive strength index (RSI) of the ND-L improved from 0.40 ± 0.06 to 0.45 ± 0.08 ($p = 0.008$; g = 0.58). Additionally, contact time in the ND-L increased significantly from 342 ± 36 ms to 375 ± 42 ms after CA performed by the dominant limb ($p = 0.001$; g = 0.66). In the elite (ELI) group, JH significantly increased from 16.4 ± 2.4 cm to 18.3 ± 3.3 cm ($p < 0.001$; g = 0.79), while RSI in the dominant limb (DL) improved from 0.47 ± 0.06 to 0.53 ± 0.07 ($p = 0.011$; g = 0.68).

Conclusions Results suggest that the examined CA effectively induces the post-activation performance enhancement in DJ among elite volleyball players, with a predominantly local impact on the limb executing the CA.

Trial registration NCT06459050 (Retrospectively registered).

Keywords Post-activation potentiation, Neuromuscular performance, Explosive strength, Isometric exercise, Unilateral movement, Plyometric training

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Introduction

Developing high levels of power output while performing specific movements is an essential component of many team sports [1], including volleyball [2]. Volleyball relies to a greater extent on jumping ability being a determinant of success in volleyball, directly influencing crucial game actions such as spiking, blocking, and serving [2]. Studies indicate that elite volleyball players exhibit superior jumping ability compared to lower-level athletes, and jump performance has been correlated with match outcomes and team rankings [3]. Given the unilateral and reactive nature of many volleyball-specific movements, optimizing single-leg jump mechanics is essential for enhancing overall athletic performance and reducing injury risk, therefore it has been suggested that athletes should be trained and tested using unilateral movements [3]. For instance, the single-leg drop jump (DJ) and split squat are often selected for training and testing purposes [4, 5].

It is generally agreed that designing the training program should aim for reliable methods to effectively facilitate the acquisition of specific motor abilities and neuromuscular adaptations [6]. The training exploiting the phenomenon of post-activation performance enhancement (PAPE) seems to be effective in achieving those adaptations and has been meticulously investigated in recent years [7–9]. This method refers to the pairing of high-effort exercise called conditioning activity (CA) with a biomechanically similar high-velocity power movement [7]. PAPE method of training proved to be beneficial in volleyball increasing countermovement jump [10], squat jump [11, 12], and many other jumping tests [13]. While there is ongoing debate regarding local and remote PAPE effect [14–16], specifically, does conditioning one limb enhance performance in the other [17, 18]?.

The potential occurrence of the remote PAPE effect is supported by plausible physiological hypotheses, such as an elevation in neural drive [7, 19] or catecholamine secretion subsequent to high-intensity CA [20]. Studies predominantly fall into two categories: those evaluating the effects of upper CA on lower body exercises and vice versa [13, 15, 16, 21], and other investigating impact of CA in contralateral limb [14, 17, 18]. For example, Bartolomei et al. [21], demonstrated that a high-intensity bench press induces a PAPE effect in the lower limbs, but not the other way around. Another study by Bartolomei et al. [15], verified that a significant increase in countermovement jump (CMJ) power output after 5 sets of single repetitions with a load of 90% 1RM in the bench press but not after 30% 1RM. Similarly, a recent study by Kolinger et al. [22] revealed no changes during elbow flexion and extension after high-intensity squats, despite contributing to increased peak torque during isokinetic knee flexion and extension. Conversely, available studies on the contralateral PAPE effect suggest a local manifestation of this phenomenon [14, 17, 18]. Wong and colleagues [18] observed a PAPE effect in the exercising arm following a CA performed by the elbow flexors of one arm. Interestingly, authors noted a performance decrease in the contralateral arm. In contrast, Power et al. [17] did not find a significant difference in DJ difference when the tested leg underwent activation through 4 repetitions of 5 s knee extension maximal voluntary isometric contractions. However, to the best of our knowledge only the protocol in study by Andrews et al. [14] has adopted a procedure closely mimicking training setting. Authors found that split squat exercise (5/2/1 repetition with 50%, 70% and 90%1RM; respectively) increased the CMJ height of the conditioned leg but provoked statistically significant CMJ height impairments in the contralateral leg with no effect in DJ height, contact time and reactive strength index (RSI). Probably, as stated by authors the PAPE effect in DJ was masked due to the high balance and coordination recruitment upon landing and taking of on one leg. Therefore, in addition to the strength level, training status, specifically the ability to perform certain exercises may determine the PAPE effect utilization.

Interestingly, to the best of the authors' knowledge, only the study protocol by Power et al. [17] assessed the effectiveness of CA performed by both the dominant and non-dominant leg. In the studies by Wong et al. [18] and Andrews et al. [14], the PAPE effect and its contralateral action were exclusively investigated through stimulation of the dominant limb. Hence, it remains unknown whether the magnitude of the PAPE effect is similar in the dominant and non-dominant limbs, and whether the potential transfer from dominant to non-dominant, and vice versa, is similar. Knowing the impact of unilateral CA on athletic performance and the contralateral effect might be useful for selecting the suitable PAPE parameters and its use in training settings appropriate to the athlete's training status. Considering inconsistent findings regarding impact of CA on contralateral effect, the purpose of this study is to evaluate the acute effects of overcoming isometric split squats on subsequent single-leg DJ performance in volleyball players. In parallel, additional factor such as training status will be considered. We assume a significant increase in DJ performance after CA performed by the same limb and a significantly higher PAPE effect in the elite athletes compared to amateurs.

Materials and methods

Experimental approach to the problem

The study was performed following CONSORT guidelines in a randomized, double-blind crossover design, where each athlete performed two experimental sessions to compare the acute effects of overcoming isometric split squats on subsequent single-leg DJ performance. Each session involved performing 3 sets of 3-second overcoming isometric split squats with a 3-minute rest between sets as a CA. However, sessions differed in terms of the limb used, dominant vs. non-dominant. A single-leg DJ for both the dominant and non-dominant limbs was performed in random order 5 min before and at the 4th and 8th minutes after completing the CA (Fig. 1). This rest time frame has been determined by recent research to be sufficient to elicit a PAPE response in various levels of athletes [15, 19].

Participants

The required sample size was determined using G*Power (version 3.1., University of Düsseldorf, Germany) based on an expected effect size of g = 0.56 [23], a statistical power of 0.8, and an alpha level of 0.05 for this study design (two-way repeated-measures ANOVA, within-between interaction), indicating a minimum of 20 participants. Ten male professional (ELI; age: 28 ± 7 years; height: 198 ± 10 cm; body mass: 92 ± 9 kg; one-repetition maximum back squat: 1.63 ± 0.15 kg/body mass; volleyball training experience: 15 ± 7 years) and ten amateur (AMA; age: 19 ± 1 years; height: 189 ± 5 cm; body mass: 87.7 ± 6.8 kg; one-repetition maximum back squat: 1.49 ± 0.21 kg/body mass; volleyball training experience: 6 ± 2 years) volleyball players participated in this study (Fig. 2). Recruitment was carried out through direct contact with professional and amateur volleyball teams in Poland. Elite players were identified and selected from teams competing in the highest Polish volleyball league, while amateur players were recruited from lower-division teams and university-level volleyball programs. Team coaches and strength and conditioning staff were approached to assist in identifying eligible athletes.

The study was conducted during the pre-season period with 48–72 h apart between sessions, ensuring that participants were in a structured training phase but not experiencing excessive fatigue from competitive play. Data collection took place at the Strength and Power Laboratory at the Academy of Physical Education in Katowice, Poland, where controlled conditions allowed for accurate and standardized assessments.

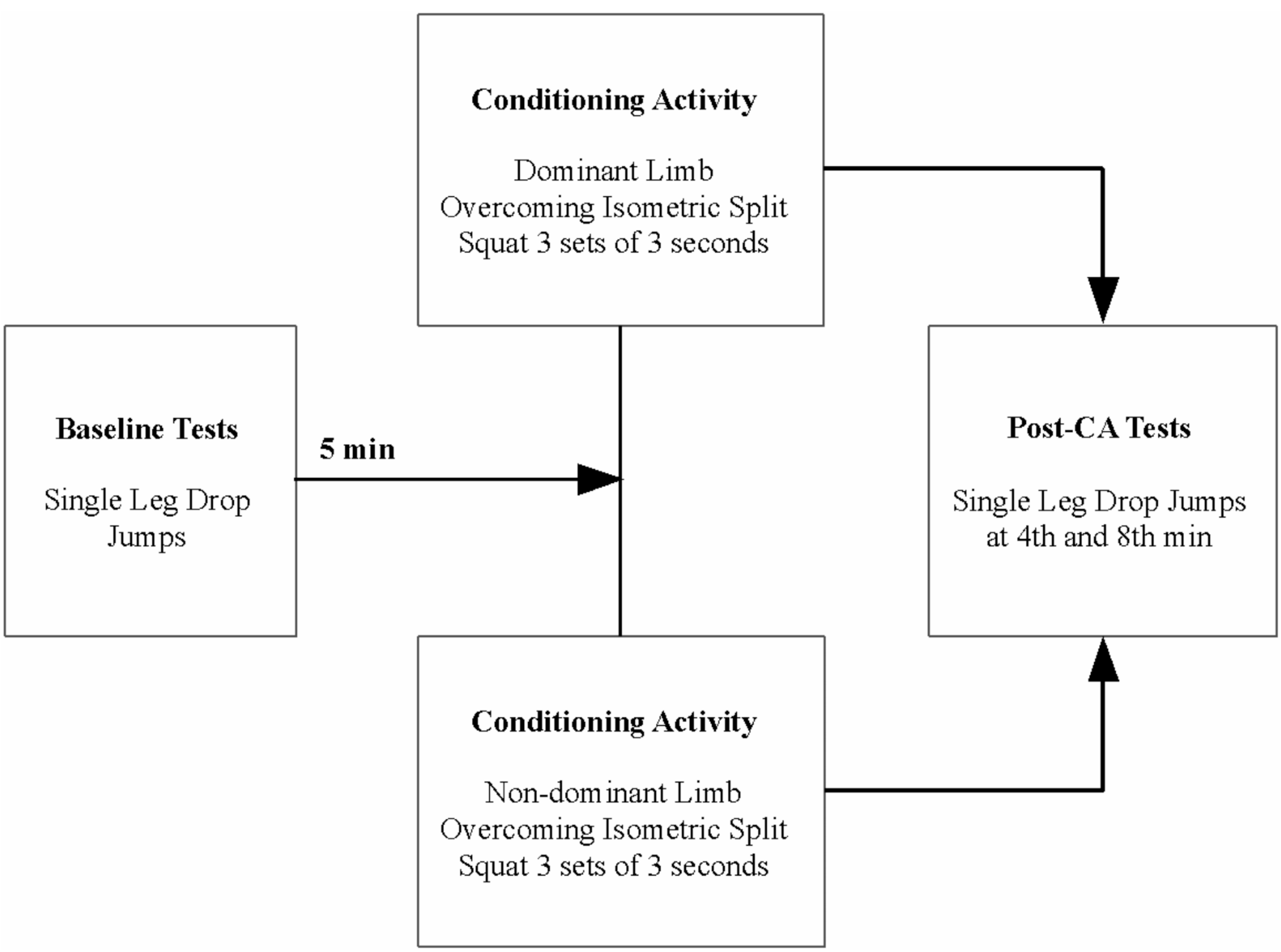

Fig. 1 Study design flowchart. CA– conditioning activity

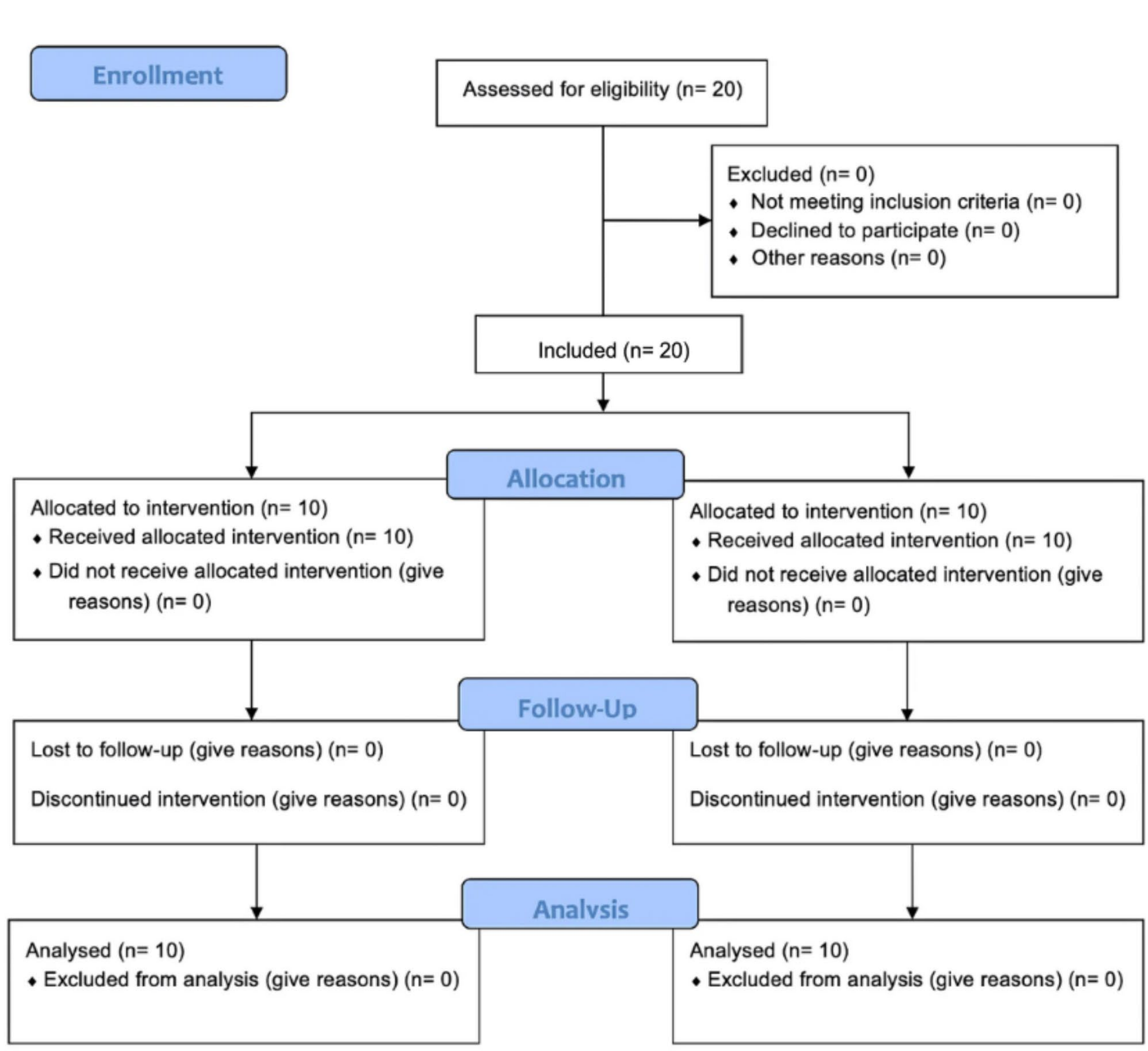

Fig. 2 CONSORT flow diagram

To ensure consistency and reliability in performance measurements, all participants wore standard volleyball training shoes meeting the following criteria: maximum sole height of 3 cm to minimize the effect of cushioning on ground reaction forces, a flat sole without excessive heel elevation to maintain natural ankle positioning. Shoes with high-impact absorption technologies (e.g., air cushions or spring systems) were not allowed to eliminate performance variability.

The inclusion criteria for both groups were as follows: (i) no lower-limb serious injury, including tendon or muscle tear, and (ii) participation in regular resistance training and competition. Additionally, to be included in the ELI group, athletes had to compete at the highest Polish volleyball league for at least two consecutive seasons. Athletes in the AMA group had to compete in junior groups outside the highest league level. Athletes were instructed to maintain their sleep hygiene and dietary habits and refrain from taking stimulants throughout the study. Tests were scheduled at the same time of day (9:00–11:00) for all testing and training sessions to avoid the effects of the circadian rhythm. The randomization was performed with an online generator (randomization.org). Each participant received a number and sequence of the sessions. Athletes were asked not to perform any additional high-intensity exercises 48-h before testing to minimize fatigue. The athletes were informed about the study's benefits and potential risks before the experiment's commencement and gave their written consent to participate. However, the athletes and the supervisor who was overseeing the training did not know about the potential result. The study protocol was approved by the Bioethics Committee for Scientific Research at the Academy of Physical Education in Katowice (3/2021) and performed according to the ethical standards of the Declaration of Helsinki 2013.

Experimental sessions

After the warm-up consisting of 5-minute cycling and dynamic exercises by 2 sets of 5 repetitions: backward lunge and reach, leg cradle, knee hug, inverted hamstring with knee drive, drop lunge and world greatest stretch, athletes performed baseline dominant and non-dominant DJ measurements in random order. Two trials of each jump from a 20 cm box with 30-second rest intervals were executed. After a 5-minute rest, athletes performed an overcoming isometric dominant or non-dominant split squat (on separate sessions) as a CA in randomized order. Limb dominance was determined based on self-report by answering a question "If you would shoot a ball on a target, which leg would you use to shoot the ball?" [24]. The overcoming isometric split squat was executed on an immovable barbell loaded with a load, preventing any concentric movement. Athletes were positioned under the individually adjusted barbell height to ensure approximately 90-degree knee extension (Fig. 3). They were instructed to "push the barbell as fast and forcefully as possible for 3 seconds". Each limb performed two DJ at the 4th and 8th minutes post-CA. The best attempt in terms of jump height from these trials was retained for further analysis to ensure a reliable measure of maximal performance.

Measurement of drop jump performance

Single leg DJ performance was assessed using dual force plates (Force Decks, Vald Performance, Australia), a validated system for measuring vertical jump kinematics and ground reaction forces with high reliability (ICC = 0.97–0.99 for jump height and 0.93–0.98 for contact time) [25]. Each athlete performed four single-leg DJ without arm swings at three time points: baseline (pre-CA) and at the 4th and 8th minutes post-CA. The single leg DJ test was performed under standardized conditions to minimize variability and ensure accurate assessment of neuromuscular performance. Athletes began each trial in a standing position on a designated box with their hands on their hips to eliminate the influence of arm swing. The drop was initiated by stepping off the box with one foot, ensuring minimal horizontal displacement during descent. Upon ground contact, athletes were instructed to rebound as quickly and explosively as possible, minimizing ground contact time while aiming for maximal jump height. The force plates recorded key jump metrics in real time, including jump height (JH), RSI, and contact time (CT). A trial was considered invalid if the athlete lifted their feet during flight, landed outside the designated force plate area, failed to maintain a neutral body position, or demonstrated an excessive countermovement upon landing. To account for training status differences and maintain ecological validity, ELI performed single leg DJ from a 40 cm box, while AMA used a 20 cm box. These heights were chosen based on standard training practices for each group and aimed to replicate their typical jump mechanics. Each athlete completed four trials per testing condition, with a 30-second rest interval between attempts. The best trial in terms of jump height was retained for further analysis, ensuring that the most representative maximal performance was used for statistical comparisons. All jumps were performed under the supervision of trained researchers to ensure adherence to standardized protocols and to provide real-time feedback on technique and execution. The instruction given to the athlete was: *"jump as high and as quick as you can".*

Statistical analysis

All statistical analyses were performed using JASP software (JASP Team version 0.18.1; macOS Sonoma 14.2.1) and were shown as means with standard deviations (± SD). Statistical significance was set at $p < 0.05$. The normality of data distribution was checked using Shapiro–Wilk tests, and Mauchly's test was used to test for the assumption of sphericity. Independent-sample t-tests were used to examine differences in basic characteristics between ELI and AMA. A single-rater intra-class correlation coefficient (ICC) and coefficient of variability (CV) were used to measure value reliability (calculated from the baseline measurements taken for each of the dependent variables) (13). The three-way mixed ANOVAs with repeated measures (2 groups [ELI, AMA] × 2 sides [DOM, N-DOM] × 2 times [PRE, BEST) were used to investigate the effects of each CA on the single leg DJ performance among elite and amateur volleyball players. When a significant main effect or interaction was found, the post-hoc tests with Tuckey correction were used to analyze the pairwise comparisons. The magnitude of mean differences was expressed with standardized effect sizes. Thresholds for qualitative descriptors of Hedge's g were interpreted as ≤ 0.20 "small", 0.21–0.79 "medium", and > 0.80 as "large" [26].

Results

A comparison of the basic anthropometric and strength characteristics between ELI and AMA volleyball players is presented in Table 1. Elite players were significantly older (28 ± 7 years vs. 19 ± 1 years, $p < 0.001$), taller (198 ± 10 cm vs. 189 ± 5 cm, $p = 0.004$), and heavier (92 ± 9 kg vs. 87.7 ± 6.8 kg, $p = 0.032$) than amateur players. Strength levels, as measured by the 1RM back squat

Fig. 3 Position during conditioning activity

relative to body mass, were also significantly higher in the ELI group (1.63 ± 0.15 kg/kg) compared to AMA players (1.49 ± 0.21 kg/kg, $p = 0.012$). In addition, volleyball training experience was significantly longer in elite players (15 ± 7 years vs. 6 ± 2 years, $p < 0.001$).

The measurement reliability was moderate to excellent for jump height (ICC > 0.63, CV = 8–9%), relative peak power (ICC > 0.55, CV = 4–6%), contact time (ICC > 0.74; CV = 3–5%), and RSI (ICC > 0.75; CV = 2–3%). Interactions and main effect of ANOVA for dependent variables are presented in Table 1.

Post-hoc pairwise comparisons for the side × time interaction showed a significant increase in jump height ($p = 0.001$; g = 0.65) and RSI ($p = 0.008$; g = 0.58) from pre to best time point in the ND-L after CA performed by the non-dominant limb (Table 2). Moreover, a significant

Table 1 Basic characteristics of elite and amateur volleyball players

Characteristics	ELI (Mean ± SD)	AMA (Mean ± SD)
Age (years)	28 ± 7	19 ± 1
Height (cm)	198 ± 10	189 ± 5
Body Mass (kg)	92 ± 9	87.7 ± 6.8
1RM Back Squat (kg/kg body mass)	1.63 ± 0.15	1.49 ± 0.21
Volleyball Training Experience (years)	15 ± 7	6 ± 2

ELI– elite; AMA– amateur; 1RM– one-repetition maximum

increase in contact time in ND-L from pre to best time point ($p = 0.001$; g = 0.66) was found after CA performed by the dominant limb. Furthermore, in the ELI group, post-hoc pairwise comparisons for the group × time interaction indicated a significant increase in jump height ($p < 0.001$; g = 0.79) and a significant RSI increase in D-L ($p = 0.011$; g = 0.68), both observed from pre to the best time point after CA performed by the dominant limb.

Table 3 presents a comparison of single leg DJ performance metrics to examine the localized and potential contralateral effects of isometric conditioning activity. In ELI, a significant improvement in jump height was observed when the same limb was used for both CA and the subsequent single leg DJ. Specifically, after CA performed by the dominant limb, JH increased from 16.4 ± 2.4 cm to 18.3 ± 3.3 cm ($p < 0.001$, g = 0.79). Similarly, JH improved following non-dominant limb CA, increasing from 13.7 ± 2.6 cm to 15.5 ± 2.7 cm ($p = 0.001$, g = 0.65). In contrast, the contralateral effect was limited, as no statistically significant improvements in JH were observed in the non-conditioned limb post-CA.

For AMA, a different response pattern was noted. JH significantly increased only when CA was performed by the non-dominant limb, rising from 11.0 ± 2.4 cm to 12.4 ± 2.4 cm ($p = 0.008$, g = 0.58). However, no significant changes in JH were observed following CA of the dominant limb.

Changes in CT further reinforce the differences between the two groups. In elite players, CT remained relatively stable following same-limb CA. However, after dominant-limb CA, CT significantly increased in the non-dominant limb ($p = 0.001$, g = 0.66). In the amateur group, CT exhibited greater variability, with no consistent patterns emerging across conditions.

Similarly, improvements RSI were more pronounced in elite players than in amateurs. In the ELI group, RSI significantly increased after dominant-limb CA, from 0.47 ± 0.06 to 0.53 ± 0.07 ($p = 0.011$, g = 0.68). The non-dominant limb also showed a significant RSI increase ($p = 0.008$, g = 0.58). Conversely, in the AMA group, RSI improved only when CA was performed with the non-dominant limb ($p = 0.021$, g = 0.264),

Discussion

The study aimed to assess the acute effects of overcoming isometric split squats on subsequent single-leg DJ performance in volleyball players, considering differences in training status. The results indicated that 3 sets of overcoming isometric 3-second split squats led to an improvement in single leg DJ height and RSI when CA and post-CA tasks were performed by the same limb in the ELI group. Additionally, a contralateral PAPE effect was observed in the ELI group, resulting in an increase in single leg DJ height performed by the limb that did not undergo the CA. However, in the AMA group, the response pattern of the PAPE effect differed, being

Table 2 Interactions and main effects of ANOVAs for all variables

Variable	Jump Height		Contact Time		RSI	
	Non-dominant CA	Dominant CA	Non-dominant CA	Dominant CA	Non-dominant CA	Dominant CA
Group × Side × Time	F = 0.497; $p = 0.49$; $\eta^2_p = 0.027$	F = 3.669; $p = 0.071$; $\eta^2_p = 0.169$	F = 0.37; $p = 0.551$; $\eta^2_p = 0.02$	F = 0.576; $p = 0.458$; $\eta^2_p = 0.031$	F = 0.132; $p = 0.721$; $\eta^2_p = 0.007$	**F = 4.428; $p = 0.05$; $\eta^2_p = 0.197$**
Side × Time	**F = 17.078; $p < 0.001$; $\eta^2_p = 0.487$**	F = 0.448; $p = 0.512$; $\eta^2_p = 0.024$	F = 2.222; $p = 0.153$; $\eta^2_p = 0.11$	**F = 13.3; $p = 0.002$; $\eta^2_p = 0.425$**	**F = 6.454; $p = 0.021$; $\eta^2_p = 0.264$**	F = 1.446; $p = 0.245$; $\eta^2_p = 0.074$
Group × Time	F = 1.142; $p = 0.299$; $\eta^2_p = 0.06$	**F = 5.738; $p = 0.028$; $\eta^2_p = 0.242$**	F < 0.001; $p = 1$; $\eta^2_p < 0.001$	F = 0.053; $p = 0.82$; $\eta^2_p = 0.003$	F = 1.217; $p = 0.284$; $\eta^2_p = 0.063$	**F = 5.315; $p = 0.033$; $\eta^2_p = 0.228$**
Group × Side	F = 0.024; $p = 0.877$; $\eta^2_p = 0.001$	**F = 8.519; $p = 0.009$; $\eta^2_p = 0.321$**	F = 0.802; $p = 0.382$; $\eta^2_p = 0.043$	F = 0349; $p = 0.562$; $\eta^2_p = 0.019$	F = 0.161; $p = 0.693$; $\eta^2_p = 0.009$	**F = 6.034; $p = 0.024$; $\eta^2_p = 0.251$**
Time	**F = 4.399; $p = 0.05$; $\eta^2_p = 0.196$**	**F = 12.779; $p = 0.002$; $\eta^2_p = 0.321$**	F = 0.038; $p = 0.847$; $\eta^2_p = 0.002$	**F = 5.182; $p = 0.035$; $\eta^2_p = 0.224$**	**F = 5.367; $p = 0.033$; $\eta^2_p = 0.23$**	**F = 4.756; $p = 0.043$; $\eta^2_p = 0.209$**
Side	**F = 10.964; $p = 0.004$; $\eta^2_p = 0.379$**	**F = 39.503; $p < 0.001$; $\eta^2_p = 0.687$**	F = 0.63; $p = 0.438$; $\eta^2_p = 0.034$	F = 1.378; $p = 0.256$; $\eta^2_p = 0.071$	**F = 10.547; $p = 0.004$; $\eta^2_p = 0.369$**	**F = 31.592; $p < 0.001$; $\eta^2_p = 0.637$**
Group	**F = 9.056; $p = 0.008$; $\eta^2_p = 0.335$**	F = 3.559; $p = 0.075$; $\eta^2_p = 0.165$	F = 0.13; $p = 0.722$; $\eta^2_p = 0.007$	F = 0.644; $p = 0.433$; $\eta^2_p = 0.035$	**F = 13.961; $p = 0.002$; $\eta^2_p = 0.437$**	F = 3.249; $p = 0.088$; $\eta^2_p = 0.153$

RSI– reactive strength index; CA– conditioning activity

Table 3 Comparison of single leg drop jump performance pre- and post-conditioning activity

		Non-dominant CA		**Dominant CA**	
		Jump Height [cm]			
		Pre-CA	**Best**	**Pre-CA**	**Best**
ELI	D-L	15.8 ± 2.2 (14.1 to 17.4)	16 ± 1.7 (14.8 to 17.2)	16.4 ± 2.4 (14.7 to 18.0)	18.3 ± 3.3* (16 to 20.7)
	ND-L	13.7 ± 2.6 (11.9 to 15.6)	15.5 ± 2.7* (13.6 to 17.5)	13.8 ± 2.2 (12.2 to 15.4)	15 ± 2.6* (13.2 to 16.8)
AMA	D-L	13.5 ± 2.8 (11.5 to 15.6)	12.7 ± 2.8 (10.7 to 14.7)	13.8 ± 4.2 (10.8 to 16.8)	13.3 ± 4.7 (10 to 16.6)
	ND-L	11 ± 2.4 (9.3 to 12.7)	12.4 ± 2.4* (10.7 to 14.2)	11.9 ± 4.0 (9.0 to 14.7)	13 ± 4.5 (9.8 to 16.3)
		Contact Time [ms]			
ELI	D-L	345 ± 28 (325 to 365)	343 ± 50 (307 to 379)	350 ± 29 (329 to 371)	345 ± 41 (315 to 374)
	ND-L	342 ± 36 (316 to 367)	345 ± 35 (320 to 370)	344 ± 37 (317 to 371)	375 ± 42* (345 to 405
AMA	D-L	348 ± 29 (327 to 369)	342 ± 29 (321 to 362)	341 ± 31 (319 to 363)	339 ± 39 (311 to 367)
	ND-L	349 ± 41 (320 to 378)	357 ± 34 (333 to 381)	333 ± 37 (307 to 359)	355 ± 45* (323 to 387)
		RSI			
ELI	D-L	0.47 ± 0.09 (0.41 to 0.54)	0.47 ± 0.07 (0.42 to 0.53)	0.47 ± 0.06 (0.42 to 0.51)	0.53 ± 0.07* (0.48 to 0.59)
	ND-L	0.40 ± 0.06 (0.36 to 0.45)	0.45 ± 0.08* (0.4 to 0.51)	0.40 ± 0.08 (0.35 to 0.46)	0.41 ± 0.08 (0.35 to 0.46)
AMA	D-L	0.39 ± 0.06 (0.34 to 0.43)	0.37 ± 0.08 (0.31 to 0.43)	0.40 ± 0.12 (0.32 to 0.49)	0.39 ± 0.13 (0.3 to 0.49)
	ND-L	0.31 ± 0.04 (0.28 to 0.34)	0.35 ± 0.07* (0.3 to 0.4)	0.36 ± 0.11 (0.28 to 0.43)	0.37 ± 0.11 (0.29 to 0.44)

* a significant difference in comparison to Pre-CA within condition, limb and group; ELI– elite; AMA - amateur; CA- conditioning activity; ND-CA– non-dominant limb conditioning activity; D-CA– dominant limb conditioning activity; D-L– dominant limb; ND-L– non-dominant limb; RSI– reactive strength index

evident only when the CA and post-CA single leg DJ were performed by the non-dominant limb.

Specifically, the results of the three-way mixed ANOVA highlight several key findings regarding the effects of overcoming isometric split squats on single-leg DJ performance. The side × time interaction ($p < 0.001$; $\eta^2 p = 0.487$) confirmed that PAPE effects were primarily local, improving single leg DJ height in the limb that performed the conditioning activity. This effect was more pronounced in elite players, who demonstrated improvements in both limbs, whereas amateur players only benefited when CA was performed on the non-dominant limb. This suggests that training experience influences the ability to utilize PAPE effectively, likely due to superior neuromuscular adaptations in elite athletes.

The group × side interaction ($p = 0.009$; $\eta^2 p = 0.321$) further supports this distinction, as ELI players consistently improved in both limbs following CA, while AMA players exhibited inconsistent responses. This may be attributed to differences in motor control and inter-limb coordination, which are more developed in experienced athletes. Additionally, the group × time interaction ($p = 0.028$; $\eta^2 p = 0.242$) revealed that jump height improvements were significantly greater in ELI players, reinforcing previous findings that trained individuals are better suited to elicit PAPE responses due to heightened neuromuscular efficiency.

In terms of contact time, a significant increase was observed in the dominant limb after CA ($p = 0.001$; $\eta^2 p = 0.66$). This suggests that while jump height improved, the underlying mechanism may involve altered movement strategies, such as increased ground contact, rather than purely enhanced explosiveness. Similarly, RSI outcomes revealed a significant improvement in the ELI group ($p = 0.033$; $\eta^2 p = 0.228$), but not in the AMA group, indicating that elite athletes were able to maintain efficient force production post-CA, whereas amateurs did not exhibit the same level of neuromuscular readiness.

There is an ongoing debate regarding the existence of the nonlocalized PAPE effect, driven by reasonable physiological hypothesis, such as an increase in neural drive or catecholamine secretion following high-intensity CA [20]. However, available studies on the remote, specifically contralateral PAPE effect suggest a local manifestation of this phenomenon [14, 17, 18]. For instance, Wong et al. [18] demonstrated a significant increase in peak torque during isokinetic elbow flexion solely in the arm that underwent CA. Likewise, Andrews et al. [14]

showed an increase in unilateral countermovement jump height after split squats but only for the limb executing the CA. Consequently, in both studies a cross effect was not observed. Similarly, in the current study, an increase in DJ height and RSI was observed during a jump executed by the limb that underwent CA in both groups, except for CA and post-CA performed by the dominant limb in the AMA group. Interestingly, an increase in DJ height was also noted during a jump performed by the non-dominant limb after CA performed by the dominant limb. This outcome may suggest a contralateral PAPE effect; however, it is essential to consider that this coincided with an increase in ground contact time during DJ and, consequently, it did not significantly affect RSI. This implies that the increase in DJ height primarily resulted from a shift in jump strategy. Additionally, it is noteworthy that the CA applied in this study was performed in a unilateral fashion, differing from the monoarticular movements in the studies by Wong et al. [18] and Power et al. [17], where isometric elbow flexion and knee extension were employed, respectively. Furthermore, in this study, an isometric split squat was performed, involving the rear limb in force production during CA. As a result, the applied CA might unintentionally induce a certain degree of stimulation in the rear limb.

In our study, ELI demonstrated a higher relative strength level, as indicated by their 1RM back squat-to-body mass ratio (1.63 ± 0.15 kg/bm) compared to AMA (1.49 ± 0.21 kg/bm). This supports the assumption that elite athletes possess superior neuromuscular readiness, which may contribute to their ability to better exploit PAPE [27]. Prior research suggests that individuals with greater strength levels are more likely to experience enhanced neuromuscular responses following a CA due to greater motor unit recruitment, increased baseline muscle stiffness, and improved capacity to tolerate high-intensity potentiation-inducing stimuli [11.28]. The findings of our study align with these observations, as ELI exhibited a more pronounced PAPE effect, particularly when performing with their dominant limb. Conversely, the PAPE response in AMA was less consistent, particularly following CA performed with the dominant limb. This variability may be attributed to their lower relative strength levels, which could reduce their ability to generate optimal neuromuscular potentiation. Additionally, it is possible that for weaker individuals, the applied isometric CA functioned more as a fatiguing stimulus rather than an effective potentiating mechanism. This could explain why, in some conditions, single leg DJ height did not exhibit a significant improvement post-CA.

Previous studies indicate that elite volleyball players exhibit superior jump biomechanics, including greater impulse generation, higher take-off velocities, and shorter ground contact times, compared to amateur players [2, 3, 5]. Additionally, research from basketball, soccer, and track & field suggests that elite athletes have greater muscle cross-sectional areas and higher rate of force development, enabling them to respond more effectively to CA and optimize jump performance [28]. These neuromuscular differences likely explain why PAPE effects were more pronounced in the ELI, whereas AMA exhibited a more inconsistent response.

In the ELI group, the local PAPE effect was evident when both CA and post-CA were performed by the same limb, either dominant or non-dominant. Conversely, in the AMA group, it was observed only in the non-dominant limb PAPE procedure. It is consistently emphasized that the training status influences the occurrence and magnitude of induced PAPE effects [8, 29], and recent studies also highlight that the type of post-CA task may have an impact [14, 25]. For example, Andrews et al. [14] revealed a PAPE effect in countermovement jump but not in the DJ. The authors suggested that this discrepancy could be attributed to the fact that DJ is a more demanding task in terms of balance and coordination, potentially masking the PAPE effect. A recent study by Krzysztofik et al. [25] also suggested that the complexity of the post-CA task may influence the magnitude of the elicited PAPE effect. The authors demonstrated an increase in countermovement jump height performed without arm swing but not with arm swing following high-intensity CA. However, surprisingly, despite the dominant limb being more efficient in performing motor tasks the PAPE effect was observed in the AMA group only in the non-dominant limb procedure. Meanwhile, in the ELI group, a significant PAPE effect occurred locally in both the dominant and non-dominant limbs. The explanation for these contradictory results between the studied groups is unknown, but may be attributed to training experience and, in the case of non-dominant procedure, may be attributed to motor acquisition as a result of repetitive DJ.

Selection of the most suitable muscle contraction type for CA is still a matter of debate. Isometric potentiation stands out as a practical and effective option, easily implemented in training settings [28]. This method eliminates the potential challenge of selecting an inappropriate intensity level while providing relevant muscular stimuli to induce the PAPE effect. Wong et al. [18] demonstrated an increase in peak torque during elbow flexion after 3 sets of 6-second isometric contractions, while Power et al. [17] noted no impact of 4 sets of 5-second knee extension on DJ performance. Comparing the CAs used by Wong et al. [18] and Power et al. [17] to the one applied in this study, it seems that repeated isometric CAs with a short duration (such as in this study, 3 sets of 3-second isometric split squats) are sufficient to induce a significant PAPE effect.

Limitations

Analyzing the results of this study, several limitations need to be considered. The applied CA was not a pure unilateral exercise, and ground reaction forces were not measured during its execution, so there is uncertainty about whether the stimulus was similar each time and to what extent the rear limb was engaged in force production. Additionally, no physiological response measurements were taken, so it is unknown which mechanisms are responsible for the observed improvement in physical performance and whether any systemic reactions occurred. Furthermore, control conditions were not taken into account, so changes in performance cannot be entirely attributed to the CA. Moreover, the relatively small sample size ($n = 20$) may limit the generalizability of the findings, particularly when comparing elite and amateur athletes. A larger sample size could provide greater statistical power and allow for more robust conclusions regarding the variability of responses across different training backgrounds.

Practical implications

Although this study focused on volleyball players, the findings have broader implications for other sports that rely on explosive unilateral movements, such as basketball, handball, soccer, and track and field events like long jump and high jump. The observed local PAPE effect suggests that overcoming isometric split squats could be effectively incorporated into warm-up routines or training protocols to enhance jump performance in athletes across various disciplines.

For sports requiring repeated unilateral jumping, such as basketball layups, soccer headers, or high jump take-offs, this method may serve as an efficient pre-competition activation strategy. Given that the ELI athletes in this study exhibited greater PAPE effects, it is likely that experienced athletes in other sports would similarly benefit from incorporating short-duration, high-intensity isometric CA into their preparation.

Moreover, the finding that PAPE was primarily a local effect rather than a systemic one suggests that coaches and practitioners should apply CA specifically to the limb that will be engaged in explosive movements. In disciplines like track and field, where take-off asymmetry is common, targeting the take-off leg with overcoming isometric exercises might help optimize performance.

Conclusions

Overcoming isometric unilateral conditioning activity enhances single-leg DJ performance, with elite athletes demonstrating a stronger and more consistent PAPE response compared to amateurs. These findings underscore the role of training experience, neuromuscular efficiency, and movement proficiency in maximizing the potentiation effect. The localized nature of the PAPE response suggests that unilateral CA can be an effective warm-up or activation strategy for explosive sports movements. These insights provide practical guidance for strength and conditioning coaches aiming to optimize jump performance in volleyball and other sports requiring unilateral explosive power.

Supplementary Information

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Supplementary Material 1

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Author contributions
Conceptualization, MS, MK and PS; methodology, MK, KM and PS; formal analysis, MK, investigation, JJ, AT and RU; data curation, JJ, AT and RU; writing—original draft preparation, MS, KM, RU and AT; writing—review and editing, AT, MS, MK; supervision, PS and MS All authors have read and agreed to the published version of the manuscript.

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Data availability
The datasets analysed during the current study are available from the corresponding author on reasonable request.

Declarations

Ethics approval and consent to participate
The study was conducted in accordance with the Declaration of Helsinki and approved by the Institutional Review Board at the Academy of Physical Education in Katowice (3/2021). Informed consent to participate was obtained from all of the participants in the study.

Consent for publication
Informed consent for publication was obtained from all participant involved in the study.

Competing interests
The authors declare no competing interests.

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References

1. Gamble P. Periodization of training for team sports athletes. Strength Cond J. 2006;28:56–66.
2. Sheppard JM, Cronin JB, Gabbett TJ, McGuigan MR, Etxebarria N, Newton RU. Relative importance of strength, power, and anthropometric measures to jump performance of elite volleyball players. J Strength Cond Res. 2008;22:758–65.
3. Pleša J, Kozinc Ž, Šarabon N. Bilateral deficit in countermovement jump and its influence on linear sprinting, jumping, and change of direction ability in volleyball players. Front Physiol. 2022;13:768906.
4. Bishop C, Perez-Higueras Rubio M, Gullon IL, Maloney S, Balsalobre-Fernandez C. Jump and change of direction speed asymmetry using smartphone apps: Between-Session consistency and associations with physical performance. J Strength Cond Res. 2022;36:927–34.

5. McCurdy K, Technique. Variation, and progression of the Rear-Foot-Elevated split squat. Strength Cond J. 2017;39:93–7.
6. Bompa TO, Buzzichelli C. Periodization training for sports. Third Edition. Champaign: Human Kinetics; 2015.
7. Blazevich AJ, Babault N. Post-activation potentiation versus Post-activation performance enhancement in humans: historical perspective, underlying mechanisms, and current issues. Front Physiol. 2019;10:1359.
8. Boullosa D. Post-activation performance enhancement strategies in sport: a brief review for practitioners. Hum Mov. 2021;22:101–9.
9. Prieske O, Behrens M, Chaabene H, Granacher U, Maffiuletti NA. Time to differentiate postactivation potentiation from performance enhancement in the strength and conditioning community. Sports Med. 2020;50:1559–65.
10. Kalinowski R, Pisz A, Kolinger D, Wilk M, Stastny P, Krzysztofik M. Acute effects of combined isometric and plyometric conditioning activities on sports performance and tendon stiffness in female volleyball players. Front Physiol. 2022;13:1025839.
11. Masel S, Maciejczyk M. Effects of Post-Activation performance enhancement on jump performance in elite volleyball players. Appl Sci. 2022;12:9054.
12. Berriel P, Cardoso GS, Costa AR, Rosa RG, Oliveira RB, Fernando H, Kruel M. Effects of postactivation performance enhancement on the vertical jump in High-Level volleyball athletes. J Hum Kinet. 2022;82:145–53.
13. Krzysztofik M, Kalinowski R, Filip-Stachnik A, Wilk M, Zajac A. The effects of plyometric conditioning exercises on volleyball performance with Self-Selected rest intervals. Appl Sci. 2021;11:8329.
14. Andrews SK, Horodyski JM, Macleod DA, Whitten J, Behm DG. The interaction of fatigue and potentiation following an acute bout of unilateral squats. J Sports Sci Med. 2016;15:625–32.
15. Bartolomei S, De Luca R, Marcora SM. May a nonlocalized postactivation performance enhancement exist between the upper and lower body in trained men?? J Strength Cond Res. 2023;37:68–73.
16. Cuenca-Fernández F, Smith IC, Jordan MJ, MacIntosh BR, López-Contreras G, Arellano R, et al. Nonlocalized postactivation performance enhancement (PAPE) effects in trained athletes: a pilot study. Appl Physiol Nutr Metab. 2017;42:1122–5.
17. Power GMJ, Colwell E, Saeterbakken AH, Drinkwater EJ, Behm DG. Lack of evidence for Non-Local muscle fatigue and performance enhancement in young adults. J Sports Sci Med. 2021;20:339–48.
18. Wong V, Yamada Y, Bell ZW, Spitz RW, Viana RB, Chatakondi RN, et al. Postactivation performance enhancement: does conditioning one arm augment performance in the other? Clin Physiol Funct Imaging. 2020;40:407–14.
19. Tillin NA, Bishop D. Factors modulating Post-Activation potentiation and its effect on performance of subsequent explosive activities. Sports Med. 2009;39:147–66.
20. Cairns SP, Borrani F. β-Adrenergic modulation of skeletal muscle contraction: key role of excitation-contraction coupling. J Physiol. 2015;593:4713–27.
21. Bartolomei S, Lanzoni IM, Fantozzi S, Cortesi M. A comparison between Non-Localized Post-Activation performance enhancements following resistance exercise for the upper and the lower body. Appl Sci. 2022;12:1639.
22. Kolinger D, Stastny P, Pisz A, Krzysztofik M, Wilk M, Tsoukos A, et al. High-Intensity conditioning activity causes localized postactivation performance enhancement and nonlocalized performance reduction. J Strength Cond Res. 2024;38:e1–7.
23. Krzysztofik M, Spieszny M, Trybulski R, Wilk M, Pisz A, Kolinger D, et al. Acute effects of isometric conditioning activity on the viscoelastic properties of muscles and sprint and jumping performance in handball players. J Strength Cond Res. 2023;37:1486–94.
24. Van Melick N, Meddeler BM, Hoogeboom TJ, Nijhuis-van Der Sanden MWG, Van Cingel REH. How to determine leg dominance: the agreement between self-reported and observed performance in healthy adults. PLoS ONE. 2017;12:e0189876.
25. Krzysztofik M, Wilk M, Pisz A, Kolinger D, Bichowska M, Zajac A, et al. Acute effects of High-Load vs. Plyometric conditioning activity on jumping performance and the Muscle-Tendon mechanical properties. J Strength Cond Res. 2023;37:1397–403.
26. Cohen J. Statistical Power Analysis for the Behavioral Sciences; Elsevier Science: Burlington, VT, USA, 2013; ISBN 978-1-483-2764-89.
27. Chiu LZF, Fry AC, Weiss LW, Schilling BK, Brown LE, Smith SL. Postactivation potentiation response in athletic and recreationally trained individuals. J Strength Cond Res. 2003;17:671–7.
28. Lim JJH, Kong PW. Effects of isometric and dynamic postactivation potentiation protocols on maximal sprint performance. J Strength Cond Res. 2013;27:2730–6.
29. Seitz LB, Haff GG. Factors modulating Post-Activation potentiation of jump, sprint, throw, and Upper-Body ballistic performances: A systematic review with Meta-Analysis. Sports Med. 2016;46:231–40.

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