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REVIEW PAPER

Effects of post-activation potentiation and post-activation performance enhancement on vertical jump performance: a systematic review

Tina Tomc Žargi[1], Alan Kacin[1]

Affiliations: [1]University of Ljubljana, Faculty of Health Sciences, Department of Physiotherapy, Ljubljana, Slovenia

Correspondence: Tina Tomc Žargi. University of Ljubljana, Faculty of Health Sciences, Department of Physiotherapy, Zdravstvena pot 5, 1000, Ljubljana, Slovenia. E-mail: tina.tomc-zargi@zf.uni-lj.si

Abstract

Post-activation potentiation (PAP) and post-activation performance enhancement (PAPE) are acute performance-enhancing responses following conditioning activity and have been widely investigated as strategies for improving explosive movements. Therefore, this systematic review aimed to examine the effects of PAP/PAPE-related conditioning protocols on vertical jump performance and to identify protocols that most effectively enhance jump height. A systematic literature search was conducted in the PubMed and PubMed Central databases. Randomized controlled trials, crossover trials, and controlled experimental studies published in English that investigated acute changes in vertical jump performance following PAP/PAPE-inducing protocols in healthy participants were included. Twelve studies involving a total of 267 participants met the inclusion criteria. Ten studies reported significant or meaningful improvements in vertical jump performance following at least one PAP/PAPE protocol. The magnitude and timing of performance enhancement were influenced by the type of conditioning activity, recovery interval, and participants' strength and training status. Greater improvements were generally observed in stronger and resistance-trained individuals, while heavy-resistance, plyometric, eccentric-overload, and flywheel-based protocols all demonstrated the potential to enhance jump performance. Recovery intervals ranging from approximately 2 to 12 minutes appeared to provide the most favourable balance between fatigue and potentiation. Overall, the findings suggest that PAP/PAPE-related conditioning can be an effective strategy for acutely enhancing vertical jump performance when conditioning activities and recovery periods are appropriately individualized. However, considerable inter-individual variability exists, highlighting the importance of selecting protocols according to athlete characteristics and performance demands.

Keywords: *post-activation potentiation, post-activation performance enhancement, vertical jump, countermovement jump, warm-up*

@MJSSMontenegro
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Introduction

Research suggests that performing resistance exercises with moderate to high loads during an athlete's warm-up can temporarily enhance muscle strength and speed (Ebben, 2006; Hodgson et al., 2005). This phenomenon is known as post-activation potentiation (PAP). Macintosh et al. (2012) define PAP as an enhanced muscle contraction in response to a given level of electrical stimulation, occurring after a short-duration, high-intensity voluntary muscle contraction. It is measured as the maximum force generated in response to supramaximal electrical stimulation. The most likely mechanism of muscle PAP is increased phosphorylation of myosin light chains and a higher recruitment rate of motor units (Ebben, 2006; Hodgson et al., 2005; Macintosh et al., 2012; Sale, 2002). As a result, there is a significant increase in muscle tension, force, and power output (Rassier & Macintosh, 2000; Tillin & Bishop, 2009).

Some studies describe other potential mechanisms of PAP, such as increased muscle temperature and blood flow, reduced pH levels in muscles, and nervous system excitation. These mechanisms are associated with a different phenomenon known as post-activation performance enhancement (PAPE). While PAP and PAPE are often used interchangeably in literature due to their similarities, they differ in their mechanism and duration; PAP has a half-life of 28 seconds and typically lasts less than 3 minutes after activation (Vandervoort et al., 1983), whereas PAPE occurs 6–10 minutes after activation and can last over 15 minutes (Bevan et al., 2010; Seitz & Haff, 2016; Wilson et al., 2013). While PAP and PAPE represent distinct physiological phenomena, inconsistent terminology and overlapping use of these concepts in the literature make clear differentiation difficult in some studies. Therefore, both PAP- and PAPE-related conditioning protocols were considered eligible for inclusion in this review. Accordingly, the term PAP is used when referring to the mechanistic concept or to the terminology used in the original studies, whereas PAP/PAPE-related conditioning protocols, performance enhancement, or PAPE are used when describing subsequent jump-performance responses.

A significant number of studies have investigated PAP/PAPE-related conditioning protocols and ways to optimize their application. However, differences in training methods, repetitions, rest intervals, and intensity make it difficult to determine the most effective conditioning protocol for increasing vertical jump height.

Vertical jump performance is strongly influenced by neuromuscular coordination and the mechanical characteristics of muscle contraction. Force production depends on initial muscle length, motor unit recruitment and firing behaviour, and the interaction between load and shortening velocity. For explosive tasks such as jumping, coordination across multiple joints and muscle groups is essential; despite multiple theoretical movement solutions, individuals tend to display broadly comparable segmental timing patterns in the final phase of push-off (Bobbert & van Ingen Schenau, 1988). The jump is commonly evaluated using the squat jump (SJ), which primarily reflects concentric performance after a static hold to minimise stretch–shortening contributions, and the countermovement jump (CMJ), which includes an eccentric–concentric stretch–shortening cycle enabling use of stored elastic energy and stretch reflex facilitation (Enoka, 2002; Sayers et al., 1999). Consequently, CMJ height typically exceeds SJ height, and a minimal SJ–CMJ difference may indicate limited utilisation of stretch–shortening mechanisms (Bavdek et al., 2014).

The purpose of this literature review is to analyse how PAP/PAPE-related conditioning protocols affect vertical jump height and to determine which protocols are most effective for enhancing vertical jump performance.

Materials and methods

The systematic literature search was conducted in the PubMed and PubMed Central (PMC) databases. The search strategy combined terms related to post-activation potentiation and vertical jump performance using Boolean operators. The following search terms were applied: ("post-activation potentiation" OR PAP OR "post-activation performance enhancement" OR PAPE) AND ("vertical jump" OR "countermovement jump" OR "squat jump"). Additional searches were performed using relevant keyword combinations identified during the screening process. The final search was conducted on 20 January 2026. The restriction to studies published from 2014 onwards was applied to focus on contemporary experimental protocols and terminology, and to capture evidence published after earlier syntheses of PAP-related performance effects.

Randomized controlled trials, crossover trials, and controlled experimental studies investigating the acute effects of conditioning activities intended to induce post-activation potentiation (PAP) or post-activation performance enhancement (PAPE) on vertical jump performance published in 2014 or later were considered eligible. Studies were included if they: involved healthy, non-injured participants; assessed vertical jump height (e.g. squat jump or countermovement jump) before and after the conditioning activity; examined acute performance effects; were available in full text; and were published in peer-reviewed journals.

Conditioning activities included heavy resistance exercise, eccentric overload or flywheel-based exercise, isometric contractions, and plyometric conditioning, provided that the protocol was explicitly designed to elicit PAP/PAPE. Studies were excluded if they: investigated chronic training adaptations; did not include a vertical jump outcome; involved injured, rehabilitating, or clinical populations; or were case reports, reviews, editorials, or conference abstracts.

Study selection

All identified records were screened in two stages: title and abstract screening followed by full-text assessment. The screening process was conducted independently by two reviewers. Any disagreements regarding study eligibility were resolved through discussion and consensus.

Data extraction

Data extraction was performed using a standardized form. Extracted data included study characteristics, participant demographics, intervention protocols, outcome measures, and main findings. The review was conducted and reported in accordance with the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines.

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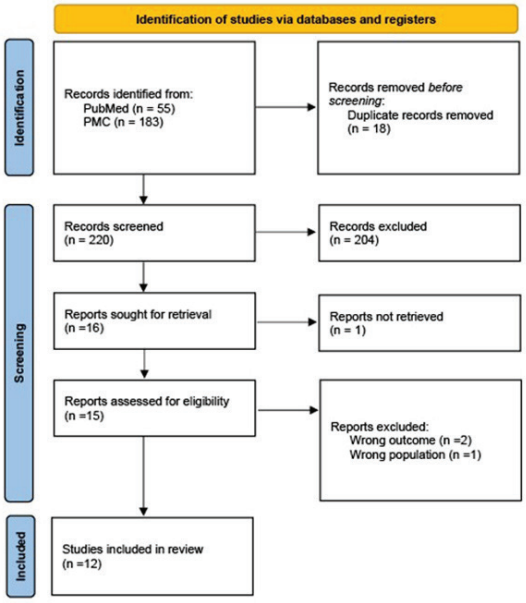


Figure 1. The PRISMA flow diagram illustrating the selection process (Page et al., 2021)

Results

Titles and abstracts were screened for relevance, followed by full-text assessment against the inclusion and exclusion criteria. Twelve studies met all eligibility criteria and were included in the qualitative synthesis. The PRISMA flow diagram illustrating the selection process is shown in Figure 1.

Across the included studies, a total of 267 participants were examined. Sample sizes ranged from 11 (Hughes et al., 2016) to 58 (Arabatzi et al., 2014) participants per study. Participants were predominantly male, with ages ranging from adolescence to young adulthood, and were generally physically active or trained athletes. Detailed participant characteristics are presented in Table 1.

Table 1. Participant characteristics

Study	participants (number, gender)	age (years ± SD)	Body mass (kg ± SD)	Body height (cm ± SD)
Arabatzi et al. (2014)	N = 58, M = 28, F = 30	10–25 *	Reported by subgroup	Reported by subgroup
Senn Sygulla & Fountaine (2014)	N = 29, M = 0, F = 29	19.9 ± 1.0	72.0 ± 8.7	174.1 ± 6.6
Hughes et al. (2016)	N = 11, M = 11, F = 0	21 ± 2	83.2 ± 10.1	179.1 ± 6.9
Bridgeman et al. (2017)	N = 12, M = 12, F = 0	25.4 ± 3.5	84.0 ± 10.1	177.2 ± 4.5
Scott et al. (2017)	N = 30, M = 30, F = 0	20.7 ± 2.0	87.1 ± 11.7	181.4 ± 6.1
Sharma et al. (2018)	N = 14, M = 14, F = 0	18.57 ± 0.94	64.79 ± 7.98	172.21 ± 5.07
Timon et al. (2019)	N = 16, M = 9, F = 7	21.8 ± 2.7	70.4 ± 12.7	172.2 ± 9.8
Kobal et al. (2019)	N = 18, M = 18, F = 0	25.42 ± 3.58	78.8 ± 10.6	175.2 ± 7.4
Mina et al. (2019)	N = 15, M = 15, F = 0	21.7 ± 1.1	77.6 ± 2.6	180 ± 10
Maroto-Izquierdo et al. (2020)	N = 20, M = 20, F = 0	23.4 ± 2.9	69.4 ± 15.4	174.0 ± 9.2
Sañudo et al. (2020)	N = 28, M = 28, F = 0	23.5 ± 5.3	74.3 ± 7.1	177 ± 10
Krzysztofik et al. (2023)	N =16, M =16, F = 0	18-19	70.1 ± 6.5	177 ± 3

Note: N = number of participants, M = male, F = female, SD = standard deviation, *divided into subgroups (preadolescents, adolescents, adults)

The included studies employed a variety of conditioning protocols designed to elicit PAP/PAPE. These included heavy resistance exercises (e.g. squats or deadlifts performed at 60–93% of one-repetition maximum), plyometric exercises (e.g. depth jumps or tuck jumps), eccentric overload protocols, flywheel-based resistance exercise, and isometric contractions. All studies incorporated a standardized warm-up prior to the conditioning activity. Conditioning protocols differed in exercise type, intensity, volume, and rest interval between the conditioning stimulus and jump performance assessment. An overview of the conditioning protocols and outcome measures is presented in Table 2.

Twelve studies examined the effects of PAP/PAPE protocols on vertical jump height using different measurement approaches. Ten of the twelve studies reported significant or meaningful improvements in vertical jump performance in at least one protocol, subgroup, or individual response analysis, whereas two studies found no significant improvement in jump height. The timing of performance measurements varied between included studies, which influenced the observed outcomes. The PAP/PAPE effect appeared strongest in trained athletes and physically stronger individuals. Table 3 provides an overview of the study results, including changes in jump height and comparisons between protocols or groups.

Table 2. Details of exercise protocols

Study	Condition / participants	Exercise protocol
Arabatzi et al. (2014)	EG1: children (10–12 y) EG2: adolescents (14–15 y) EG3: young adults (20–25 y) CG: control	8-min warm-up; 15-min rest; CA: 3 × 3-s maximal isometric half-squats at 90° knee flexion, with 2-min intervals; control: passive rest.
Senn Sygulla & Fountaine (2014)	Women athletes, out of competition season (n = 29)	Back squat protocol: 5 reps at 50% 1RM, 5 reps at 60% 1RM, 3 reps at 75% 1RM, and 3 reps at 90% 1RM; 5-min rest.
Bridgeman et al. (2017)	Strength-trained men	1 set of 5 DJs from individual optimal drop height: BM only, +10%, +20%, or +30% BM as AEL; CMJ assessed 2, 6, and 12 min post-CA.
Scott et al. (2017)	Rugby league players; BSq, HBD, and control conditions	1 set of 3 reps at 93% 1RM of either BSq or HBD; control: no CA; CMJ assessed pre and every 2 min up to 16 min post-CA.
Kobal et al. (2019)	Highly trained men	Four randomized HS conditions: 1RM, 3RM, 5RM, and 60% 1RM; CMJ assessed before and 4 min after each set.
Mina et al. (2019)	Active men; FWR and VR conditions	3 BSq reps at 85% 1RM using either FWR or VR with elastic bands; VR: 35% of total load from bands; CMJ assessed 30 s, 4, 8, and 12 min post-CA.
Sañudo et al. (2020)	Trained men; FW and TRA conditions	TRA: 3 BSq reps at 90% 1RM; FW: 3 reps plus 1 initial repetition, using inertia matched to the mean propulsive velocity at 90% 1RM.
Hughes et al. (2016)	Resistance-trained men	AEL: 6 drops from 60 cm with +5% BM using a weighted vest; comparator: BSq conditioning protocol using 3RM; CMJ assessed 6 min post-CA.
Timon et al. (2019)	EG1: traditional half squat EG2: inertial flywheel half squat Physically active participants	Traditional HS and inertial flywheel HS; both: 3 × 6 reps at the load that maximized power, with 3-min rests; SJ assessed 4, 8, and 12 min post-CA.
Maroto-Izquierdo et al. (2020)	Physically active men	Flywheel: 1 set of 6 maximal high-intensity flywheel HS reps; control: 6 maximal CMJs; CMJ assessed 4, 8, 12, 16, and 20 min post-CA.
Sharma et al. (2018)	EG1: heavy resistance protocol EG2: plyometric protocol Collegiate soccer players	RES: 10 single back half-squat reps at 90% 1RM; PLY: 40 jumps; CMJ assessed 1 and 10 min post-CA.
Krzysztofik et al. (2023)	EG1: high-load resistance EG2: plyometric conditioning Amateur male soccer players	HL: 3 × 3 half back squats at 85% 1RM; PLY: 3 × 5 tuck jumps; control: no CA; CMJ and CMJa assessed 3, 6, and 9 min post-CA.

Note: CG = control group/condition; EG = experimental group/condition; AEL = accentuated eccentric loading; BM = body mass; BSq = back squat; CA = conditioning activity; CMJ = countermovement jump; CMJa = countermovement jump with arm swing; DJ = drop jump; FW = flywheel condition; FWR = free-weight resistance; HBD = hex bar deadlift; HL = high-load condition; HS = half-squat; PLY = plyometric condition/protocol; RES = heavy-resistance protocol; RM = repetition maximum; SJ = squat jump; TRA = traditional free-weight resistance condition; VR = variable resistance.

Table 3. Study outcomes

Study	Outcome Measures	Within-Group Comparison	Between-Group Comparison
Arabatzi et al. (2014)	SJ height; pre / 20 s / 4 min post	SJ ↑ only in adult men at 20 s and 4 min ($p < 0.01$).	PAP/PAPE response age- and sex-dependent.
Senn Sygulla & Fountaine (2014)	SSJ height; pre / 5 min post; 3 maximal jumps	No overall performance enhancement ($p = 0.279$); volleyball players showed power ↓ ($p = 0.008$).	Time × team interaction: $p = 0.022$.
Bridgeman et al. (2017)	CMJ height; pre / 2 / 6 / 12 min post	CMJ ↑ after 20% AEL ($p < 0.001$); CMJ higher at 2 and 6 min than 12 min ($p < 0.001$ and $p \leq 0.05$).	20% AEL > other loading conditions ($p < 0.001$).
Scott et al. (2017)	CMJ height / PPO; pre / every 2 min up to 16 min post	CMJ height NS; PPO ↑ after HBD at 2–6 min ($p \leq 0.05$).	HBD > BS for PPO ($p \leq 0.05$); strength groups NS.
Kobal et al. (2019)	CMJ height; pre / 4 min post; 3 sets	Individual CMJ ↑ across different loads/sets.	No clearly superior protocol; high individual variability.
Mina et al. (2019)	CMJ height; pre / 30 s / 4 / 8 / 12 min post	VR: CMJ ↑ at all time points ($p < 0.05$); FWR: NS.	VR > FWR ($p < 0.05$).
Sañudo et al. (2020)	CMJ height; pre / 4 min post	CMJ ↑ after both FW and TRA ($p < 0.001$).	No clear between-condition difference for CMJ.
Hughes et al. (2016)	CMJ height; pre / 6 min post	AEL: CMJ ↑ ($p = 0.03$); BSq: NS ($p = 0.32$).	Condition × time interaction: $p = 0.02$; AEL > BSq.

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Table 3. Study outcomes

Study	Outcome Measures	Within-Group Comparison	Between-Group Comparison
Timon et al. (2019)	SJ height; pre / 4 / 8 / 12 min post	Flywheel: SJ ↑ ($p = 0.004$); traditional squat: NS.	Flywheel > traditional squat at 4 and 8 min ($p = 0.012$ and $p = 0.005$).
Maroto-Izquierdo et al. (2020)	CMJ height; pre / 4–20 min post	Flywheel: CMJ ↑ at 4–20 min ($p < 0.05$).	Flywheel > control ($p < 0.05$).
Sharma et al. (2018)	CMJ height; pre / 1 / 10 min post	PLY: CMJ ↑ at 1 min ($p = 0.004$) and 10 min ($p = 0.001$).	PLY > RES for CMJ ($p < 0.001$ for time × protocol).
Krzysztofik et al. (2023)	CMJ / CMJa height; pre / 3 / 6 / 9 min post	PLY: CMJ ↑ ($p = 0.001$); HL: no clear CMJ improvement; CMJa NS.	PLY > HL for CMJ ($p = 0.024$).

Note: AEL = accentuated eccentric loading; BS = back squat; BSq = back squat protocol; CA = conditioning activity; CG = control group/condition; CMJ = countermovement jump; CMJa = countermovement jump with arm swing; EG = experimental group/condition; FW = flywheel condition; FWR = free-weight resistance; HBD = hex bar deadlift; HL = high-load condition; NS = not significant; PAP = post-activation potentiation; PAPE = post-activation performance enhancement; PLY = plyometric condition/protocol; PPO = peak power output; RES = heavy-resistance protocol; RFDpeak = peak rate of force development; SJ = squat jump; SSJ = static squat jump; TRA = traditional free-weight resistance condition; VR = variable resistance.

Discussion

This review included twelve studies investigating the effects of PAP/PAPE protocols on vertical jump performance. Ten studies reported significant or meaningful improvements in jump performance in at least one protocol, subgroup, or individual response analysis, whereas two studies reported no measurable improvement in jump height. Overall, the findings indicate that the effectiveness of PAP/PAPE may be influenced by participant strength level, training status, sex, age, type of conditioning activity, and the recovery interval between the conditioning stimulus and subsequent performance testing. It should also be noted that many of the observed performance enhancements likely reflect post-activation performance enhancement (PAPE) rather than strictly defined PAP mechanisms.

Muscle strength and training status appear to influence the PAP/PAPE response, although the evidence is not fully consistent. Several studies included resistance-trained or stronger participants and reported positive jump-height responses following conditioning activity (Bridgeman et al., 2017; Hughes et al., 2016; Kobal et al., 2019; Mina et al., 2019; Sañudo et al., 2020). Bridgeman et al. (2017) included participants capable of squatting at least 1.5 times their body mass, while Kobal et al. (2019) included highly trained participants capable of lifting twice their body mass in the half squat. These findings suggest that greater neuromuscular capacity may facilitate PAP/PAPE expression. However, the relationship between strength and potentiation is not uniform. Sañudo et al. (2020) reported improvements in both stronger and weaker participants, whereas Scott et al. (2017) found no significant differences between strength groups. Considerable inter-individual variability was also reported across studies, indicating that strength alone does not fully explain the PAP/PAPE response.

Few included studies examined PAP/PAPE responses in female participants, and only a limited number allowed sex-related interpretation. Arabatzi et al. (2014), Senn Sygulla and Fountaine (2014), and Timon et al. (2019) included female participants, but only Arabatzi et al. directly examined age- and sex-related responses. Neither Arabatzi et al. nor Senn Sygulla and Fountaine demonstrated a clear improvement in vertical jump height in female participants, although Arabatzi et al. reported RFDpeak changes in adult women. Current evidence is therefore insufficient to determine whether sex independently moderates PAP/PAPE responses, particularly because training status and strength level may also influence outcomes.

Age-related differences were mainly reported by Arabatzi et al. (2014), who found that SJ-height potentiation was evident only in adult men, whereas RFDpeak responses were observed in adult groups and adolescent males. These findings suggest that neuromuscular development, maturation, and training exposure may influence PAP/PAPE expression. However, because few included studies directly compared age groups, conclusions regarding age-related effects remain limited.

The type of conditioning activity plays a key role in determining PAP/PAPE effectiveness. Resistance-based protocols, particularly squat or deadlift variations performed at moderate to high intensities, were frequently used across the included studies. Positive responses were reported after maximal isometric half-squats, heavy back squats, hex bar deadlifts, and variable-resistance squats, although the magnitude and timing of the response differed between studies (Arabatzi et al., 2014; Scott et al., 2017; Mina et al., 2019). Kobal et al. (2019) further showed that responses to different half-squat loads and set configurations were highly individual, suggesting that no single resistance-based protocol can be considered universally optimal. These findings support the importance of adjusting load, volume, and recovery interval to the characteristics of the athlete.

Alternative conditioning methods also showed potential for enhancing vertical jump performance. Mina et al. (2019) reported greater improvements following variable-resistance squats using elastic bands compared with free-weight resistance, possibly due to a more favourable loading profile during the movement. Flywheel-based protocols also produced positive responses, with Sañudo et al. (2020), Timon et al. (2019), and Maroto-Izquierdo et al. (2020) reporting improvements in jump performance following flywheel conditioning. In addition, Hughes et al. (2016) showed that accentuated eccentric loading enhanced CMJ performance more effectively than a traditional back squat protocol. Overall, these findings suggest that eccentric-overload, flywheel-based, and variable-resistance methods may represent effective alternatives to traditional heavy-resistance conditioning activities.

Plyometric-based PAP/PAPE protocols also appear to

be effective, particularly when the conditioning activity is mechanically similar to the subsequent jump task. Bridgeman et al. (2017) reported improved CMJ performance after loaded drop jumps, while Sharma et al. (2018) found that a plyometric protocol produced greater CMJ improvements than a heavy-resistance protocol in collegiate soccer players. Krzysztofik et al. (2023) similarly reported a greater CMJ response after plyometric conditioning than after high-load squats. These findings suggest that plyometric conditioning may provide a practical and time-efficient alternative to traditional heavy-resistance PAP/PAPE protocols, especially in applied sport settings where equipment availability, fatigue management, and warm-up duration are important.

Although heavy-resistance, plyometric, flywheel-based, and eccentric-overload protocols all appear promising, the current evidence does not support identifying one universally superior conditioning modality. Instead, the considerable inter-individual variability reported across studies supports individualized selection of exercise type, load, volume, and recovery duration.

The optimal recovery interval between the conditioning activity and performance testing is another key determinant of PAP/PAPE expression. While classical PAP mechanisms may occur within seconds (Vandervoort et al., 1983), applied performance improvements typically occur after longer recovery periods and may more closely reflect PAPE. The studies included in this review suggest that favourable responses can occur between approximately 2 and 12 minutes after conditioning activity. However, this range should not be interpreted as a single optimal recovery window. Rather, it likely reflects the interaction between conditioning modality, fatigue, training status, and individual recovery characteristics. Shorter intervals may be effective after some plyometric or eccentric-overload protocols, whereas heavy-resistance protocols may require longer recovery to balance potentiation and fatigue.

From an applied perspective, PAP/PAPE should be viewed primarily as an individualized warm-up strategy rather than a standardized protocol suitable for all athletes. Coaches and practitioners should consider the athlete's strength level, training background, type of subsequent explosive task, and available recovery time when selecting the conditioning activity. The current evidence supports testing different combinations of exercise type, load, volume, and recovery interval within individual athletes, rather than assuming that one modality or recovery duration will be optimal for all performers.

This review has several limitations. The number of included studies was relatively small, and substantial methodological heterogeneity was present across studies in terms of protocol design, participant characteristics, recovery intervals, and outcome measures. Most studies included male participants, limiting the generalisability of findings to female athletes. In addition, the literature search was limited to PubMed and PubMed Central; therefore, relevant sport science studies indexed only in other databases, such as SPORTDiscus, Scopus, or Web of Science, may have been missed. Finally, the methodological quality or risk of bias of the included studies was not formally assessed. The findings should therefore be interpreted as a descriptive qualitative synthesis rather than as evidence weighted according to methodological quality.

Conclusions

In summary, PAP/PAPE can be an effective strategy for enhancing vertical jump performance, particularly in trained and stronger individuals. However, responses are highly dependent on individual characteristics and protocol design. PAP/PAPE should therefore be considered a context-dependent performance strategy rather than a universally applicable intervention. Further research is needed to develop more standardised protocols and to better understand individual variability in response.

Conflicts of Interest

The authors declare no conflict of interest.

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