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Systematic Review

Acute Effects of Different Conditioning Activities on the Post-Activation Performance Enhancement in Athletes' Jumping and Sprinting Performances: A Systematic Review and Meta-Analysis

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Abstract: This meta-analysis assessed the impact of three induction methods on athletes' jump and sprint performances. Experimental research on the acute effects of exercise intervention on the Post-Activation Performance Enhancement (PAPE) of jumping and sprinting performances in athletes was searched using the Web of Science, PubMed, and Embase databases. The meta-analysis results show that, when employing resistance exercises as Conditioning Activities (CAs) for enhancing jumping performance, there are statistically significant differences in favor of utilizing resistance exercises as CAs (Hedges's $g = 0.2$, 0.2, and 0.23; 95%CI: (0.05, 0.34), (0.02, 0.39), and (0.05, 0.41); $p < 0.05$). In contrast, no significant differences were detected when plyometric exercises or mixed exercises were compared pre-intervention ($p > 0.05$). In terms of sprint performance, when employing resistance exercises as CAs, the effect sizes were −0.11, −0.44, and −0.32, respectively. Their corresponding 95%*CIs* were (−0.22, 0.00), (−0.63, 0.25), and (−0.50, −0.13), with all p-values < 0.05, indicating statistically significant differences favoring the utilization of resistance exercises as CAs. However, no significant differences were noted when comparing plyometric or mixed exercises to pre-intervention ($p > 0.05$). In conclusion, compared with plyometric exercises and mixed exercises, resistance exercises had a more significant effect on athletes' jumping and sprinting performances.

Keywords: post-activation performance enhancement; jump performance; sprint performance; meta-analysis

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1. Introduction

Post-Activation Performance Enhancement (PAPE) stands as a central focus in the field of sports kinesiology, delineating a physiological phenomenon wherein an athlete engages in a brief, near-maximal-intensity regulatory activity known as a Conditioning Activity (CA). Such activity elicits internal physiological alterations, including the phosphorylation of myosin regulatory light chains, heightened recruitment capacities of higher-order motor units, and a reduction in pennation angles during muscle contractions [1]. These changes culminate in an acute enhancement of sport performance. Given the rapid improvement in muscular force generation efficiency it provides, PAPE has been extensively incorporated into sports requiring high explosive strength [2], with its effects commonly assessed through jump or sprint performance tests. Numerous studies have confirmed that athletes in sports like rugby, football, weightlifting, sprinting, handball, and swimming [3–6] can enhance abilities such as short-distance sprints [3,7–9] and jumps [10] by employing PAPE during their warm-up routines prior to training or competing.

The efficacy of PAPE is contingent upon CA selection [11]. Contemporary research commonly employs various methodologies, including resistance exercises (such as barbell squats, barbell hip thrusts, and barbell hang cleans), plyometric exercises (such as depth jumps, hurdle hops, and ankle jumps), and mixed exercises (combinations of resistance exercises with plyometric exercises or resistance exercises with sprint exercises). However, a synthesis of related research findings indicates that divergences are present in the PAPE responses elicited by different CAs, which are primarily manifested in four aspects. (1) In investigating the impact of resistance exercise protocols on jump performance, Villalon et al. allocated volleyball players to engage in 90% of their 1RM half squats [12], while Mitchell et al. instructed rugby players to perform squats at 5RM intensity [13]. Both interventions led to notable improvements in the athletes' Countermovement Jump (CMJ) heights. However, such findings appear to conflict with those of Ferreira et al. [14] and Castro et al. [15], who observed no change in Taekwondo athletes' CMJ heights following squat exercises. In studies concerning sprint performance, Krčmár et al. [16], Hadjab et al. [17], and Rouissi et al. [18] noted that squat exercises effectively improved the 10 m and 30 m linear sprint speeds of basketball and football players. Conversely, Fernández et al. argued that administering squats or hip thrust exercises at 85% of 1RM did not yield significant improvements in acute sprinting outcomes among adolescent tennis players [19]. Additionally, Lim et al. found that three different variations in squat exercises failed to produce significant enhancements in the 30 m sprint performances of high-level athletes [20]. (2) In studies investigating the effects of plyometric exercise protocols on jump performance, Tobin and colleagues noted a significant improvement in subsequent CMJ outcomes among rugby players following a regimen of plyometric exercises [21]. In contrast, Dello and others found no significant improvement in jump capabilities following plyometric exercises in young athletes involved in team sports [22]. In focusing on sprint performance, research by Vanderka et al. [23] and Sener et al. [24] supported the notion that pre-competition plyometric exercises can improve subsequent linear sprint abilities in athletes of track and field, and field hockey, respectively. Kümmel and colleagues noted that depth jumps may enhance the jump performance of elite sprinters, yet seemed to have minimal impact on sprint times [25]. Additionally, Dello found that linear sprint performance could actually decrease after youth athletes perform depth jump exercises [22]. (3) Regarding the impact of mixed-exercise protocols on jump performance, research conducted by Kalinowski et al. suggested that incorporating a combination of squat and jump exercises in training protocols can lead to improvements in CMJ performance among female volleyball athletes [26]. However, research by Papla et al. [27] and Santos et al. [28] suggested that mixed exercises, when used as CAs, fall short of improving jumping performance in basketball athletes. In sprint performance studies, Matusiński et al. maintained that resistance exercises coupled with sprint exercises can significantly boost the 20 m sprint times of elite female sprinters [29]. Meanwhile, the findings by Whelan et al. [30] and Winwood et al. [31] indicated no substantial enhancement in short-distance sprint performance following mixed exercise. Comparative studies on PAPE effects induced by resistance exercises, plyometric exercises, and mixed exercises are scarce, and the findings are contradictory. Notably, Seitz and Haff's [32] research focused primarily on amateurs and lacked thorough research on athletes. Saez et al. posited that resistance exercises yield a superior PAPE response compared to plyometric exercises [33]. At the same time, Esformes et al. suggested there was no significant difference in PAPE outcomes between resistance and plyometric exercises [34]. On the other hand, there has been limited research conducted to determine which of the three basic PAPE induction patterns is most effective for enhancing athletes' jumping sprints. Furthermore, the results of existing studies are inconsistent. A recent review of relevant meta-analyses also revealed a scarcity of PAPE studies specifically focused on sprint ability [35–37].

In conclusion, it is clear that resistance exercises, plyometric exercises, and mixed exercises can all induce PAPE in athletes prior to competition or training sessions. This study focused on the population of athletes to induce PAPE in these three ways. However, consensus on the outcomes of such CAs remains elusive, and no definitive proof exists to affirm the superiority of one particular method for achieving optimal PAPE effects. By conducting a meta-analysis on experiments related to PAPE, the current study aims to explore the acute effects of three CAs on the leaping and sprinting abilities of athletes. On this basis, we investigate the most effective approaches among these three options, so as to serve as a reference for coaches developing a training plan and athletes organizing a warm-up exercise.

2. Methods

This study adheres to the international guidelines of meta-analysis as outlined in the PRISMA statement [38], selecting and employing research methodologies accordingly. Moreover, the original protocol was prospectively registered with the International Prospective Register of Systematic Reviews (PROSPERO) in February 2024 (registration number: CRD42024506345).

2.1. Inclusion and Exclusion Criteria

2.1.1. Inclusion Criteria

The PICOS guidelines were followed in developing the screening criteria.

Type of study: Experimental studies on the impact of acute physical intervention on athletic performance in jumping and sprinting. (1) Participants: healthy athletes, both professional and amateur, with no restrictions on age, gender, level, discipline, ethnicity, or nationality. Participants should be free from psychiatric anomalies, severe perception disorders, musculoskeletal diseases, surgical history, or significant organic diseases. (2) Intervention Measures: ① At least one experimental group must utilize resistance exercises, plyometric exercises, or mixed exercises (resistance exercises combined with plyometric exercises, resistance exercises combined with sprint exercises) as CAs; ② Acute intervention (within 30 min); ③ Intensity of resistance exercises assessed by %1RM or RM, while plyometric exercise intensity evaluated by the number of jumps or drop heights. (3) Outcome Indicators: Based on the research objectives, the CMJ height (in centimeters) is chosen as the outcome indicator for jumping ability; sprint time (in seconds) is the outcome measure for sprinting capacity.

2.1.2. Exclusion Criteria

(1) Non-English literature; (2) Non-acute interventions; (3) Participants are not athletes; (4) Interventions that are not free weights or resistance exercises; (5) Duplicate publications or those of low scholarly quality; (6) Studies with incoherent data descriptions, which cannot be calculated or are difficult to extract from graphical presentations.

2.2. Search Strategy

Comprehensive searches were conducted in three databases, PubMed, Embase, and Web of Science, to gather information on the impact of acute exercise interventions on athletes' jumping and sprinting abilities. The search included all records from the creation of each database until 14 February 2024. The search strategy is as follows (see Supplementary File S1 for details).

2.3. Literature Screening, Data Extraction, and Quality Assessment

2.3.1. Literature Screening

Two researchers independently and blindly reviewed the literature retrieved from the databases. The EndNoteX9 software was utilized to manage the references. Preliminary exclusions were made based on the reading of titles and abstracts. The full text of the qualified articles was then downloaded and meticulously reviewed for selection.

2.3.2. Data Extraction

Two researchers followed standardized procedures and forms for extracting the relevant information from the literature during the screening process. We discussed any disparities with the third researcher and decided whether to incorporate them into that report. This mainly included basic information about the article (such as first author and year of publication), participant demographics (such as gender ratio, number of males and females, sports discipline, age, etc.), intervention plans, recovery periods, and outcome measures (selection of trial test data, which are accessible), noting that the trial data for outcome measures must be directly or indirectly obtainable from the authors; otherwise, they were excluded.

2.3.3. Quality Assessment Section

The PEDro scale was employed to assess the quality of the studies in randomized controlled trials [39], evaluating the research quality across 11 different domains: (1) clarity of eligibility criteria, (2) random allocation, (3) allocation concealment, (4) baseline similarity of groups, (5) participant blinding, (6) therapist blinding, (7) blinding of outcome assessors, (8) measures of at least one key outcome for more than 85% of subjects, (9) compliance with the allocated intervention, (10) reporting of between-group statistical comparisons for at least one key outcome, and (11) provision of point measures and measures of variability for at least one key outcome. The assessment criteria are as follows: 1 point for each item satisfied from items 2 to 11, with a total score of 10 points. Score ranges are designated as follows: <4 points indicates low quality, 4–5 points indicates moderate quality, 6–8 points indicates high quality, and 9–10 points indicates excellent quality. For non-randomized controlled trials, the ROBINS-I 2.0 standard was used for the quality assessment [40]. Seven aspects were appraised using the ROBINS-I method: (1) confounding bias, (2) selection bias of participants, (3) classification of interventions bias, (4) deviations from intended interventions, (5) missing data, (6) measurement of outcomes bias, and (7) selective reporting bias. These were judged as “low risk of bias”, “moderate risk of bias”, “high risk of bias”, “critical risk of bias”, and “risk of bias unclear”.

2.4. Data Processing Section

Stata 17.0 software was used for the meta-analysis of effect sizes, heterogeneity testing, sensitivity analysis, and the creation of forest plots for all included literature outcomes. As all outcomes in the included studies were continuous variables with the same measurement units, Hedges’s g was chosen for statistical effect size estimation along with a computation of a 95% confidence interval (CI). Statistical heterogeneity was tested using the I^2 statistic, adopting either a fixed-effects or a random-effects model based on the level of heterogeneity: 0%, 25%, 50%, and 75% correspond to no, low, moderate, and high heterogeneity, respectively. Following Cochrane’s suggestion, it is recommended that an I^2 should not exceed 40% for acceptable heterogeneity, in which case a fixed-effects model is used for analysis; otherwise, a random-effects model is implemented. Further, subgroup analysis is used to explore sources of heterogeneity [41]. Publication bias was both quantitatively and qualitatively assessed using Egger’s test and funnel plots, with a significance level set at p-value < 0.1 [42]. For the other statistical tests, a significance level was set at p-value < 0.05.

3. Results

3.1. Literature Search Results

The literature search conducted across the PubMed, Embase, and Web of Science databases yielded a total of 4785 relevant articles. Specifically, 1864 were sourced from PubMed, 1209 were sourced from Embase, and 1730 were sourced from Web of Science. After the elimination of duplicate studies, the titles and abstracts were screened, resulting in 102 articles being preliminarily selected. A full-text screening further narrowed the field, excluding studies that did not meet the inclusion criteria. Six of these articles’ entire texts could not be obtained, 12 lacked the requisite data for extraction, and 58 did not align with the research’s subject. Ultimately, 26 articles were deemed suitable for inclusion in the meta-analysis (see Supplementary File S2 for details).

3.2. Basic Characteristics of Included Studies

The basic information included in this study is as follows (see Supplementary File S3 for details), which encompassed a total of 378 subjects, all of whom were athletes. The studies were published between 2014 and 2023. The included literature contained comprehensive details of the exercise interventions, including induction methods, intensity and volume of exercise, as well as recovery time. The outcomes measured were CMJ height and sprint times.

3.3. Quality Assessment Results of Included Studies

The PEDro scale was utilized to appraise the quality of the randomized controlled trials (RCTs) included in our review. The findings of the quality assessment indicated that one study was deemed to be of high quality, while twelve were considered to be of moderate quality. Overall, the quality of the included studies was deemed to be reliable (refer to Supplementary File S4). Additionally, 13 non-randomized controlled trials were included, all of which reported specific requirements and criteria. Since the studies involved human exercise intervention trials, they inherently carried a high risk of bias related to the intended interventions. However, the inclusion criteria for the subjects were clear, and the subjects were able to complete the study interventions as planned, with comprehensive reporting of the results (refer to Supplementary File S5).

3.4. Results of the Meta-Analysis

3.4.1. Meta-Analysis Results on Jump Performance

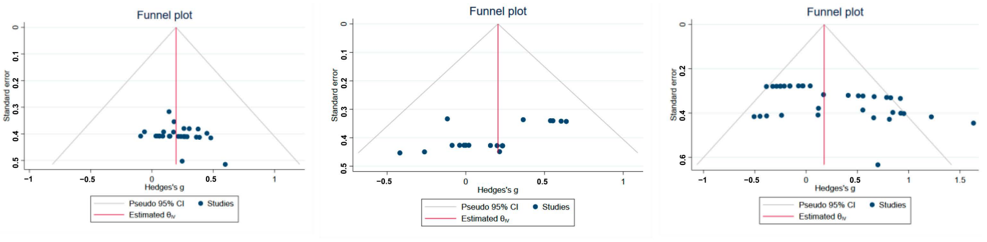
Of the 26 studies included in the final analysis, 17 studies, encompassing a total of 252 subjects, compared the acute effects of different CAs on the CMJ height, as shown in Supplementary Files S6–S8. The heterogeneity test results for Supplementary Files S6 and S7 indicated $I^2 = 0\%$, suggesting no heterogeneity among the studies; hence, a fixed-effects model was utilized for the analysis. On the other hand, Supplementary File S8 showed $I^2 = 58.08\%$, indicating the presence of heterogeneity, which led to the employment of a random-effects model for the analysis. The three forest plots signify that the PAPE from the exercise interventions effectively enhanced CMJ height for the athletes [Hedges's $g = 0.2$, 0.2, and 0.23; 95%CI: (0.05, 0.34), (0.02, 0.39), and (0.05, 0.41); $p = 0.01$, 0.03, and 0.01 (<0.05)].

Subgroup analyses of the CAs were executed, differentiating among resistance exercises, plyometric exercises, and mixed exercises. The results of the subgroup analyses for Table 1A–C revealed that resistance exercises as a CA can effectively increase CMJ height in athletes [$p = 0.003$, 0.032, and <0.001 (<0.05)]. The plyometric exercises' p-values = 0.154 and 0.805 (>0.05), whereas Table 1C showed a significant difference with a p-value = 0.027 (<0.05); however, the negative effect size (Hedges's $g = -0.177$) and 95%CI (-0.335, -0.020) indicated a decrease in CMJ height post-intervention. The mixed exercises' p-values = 0.409 and 0.429 (>0.05), indicating that neither plyometric nor mixed exercise interventions acutely enhanced CMJ height in athletes effectively.

The funnel plot results were not perfectly symmetrical, as illustrated in Figure 1A–C. The Egger's test for Figure 1A found no significant publication bias ($p = 0.622 > 0.1$). In Figure 1B, the Egger's test indicated the presence of publication bias ($p = 0.03 < 0.1$); however, after applying the trim-and-fill method, this change was not significant, and the results were considered acceptable [Hedges's $g = 0.204$; 95%CI: (0.198, 0.516)]. Conversely, in Figure 1C, the Egger's test revealed a significant publication bias ($p = 0.0006 < 0.1$); after the trim-and-fill method was employed, which was a significant alteration, the results should be interpreted with caution [Hedges's $g = 0.232$; 95%CI: (0.059, 0.405) to Hedges's $g = 0.035$; 95%CI: (-0.035, 0.234)].

Table 1. (**A**) Different CAs for athletes' CMJ height PAPE sub-group analysis (baseline−controlled, single-arm studies); (**B**) Different CAs for athletes' CMJ height PAPE sub-group analysis (non-baseline−controlled studies); (**C**) Different CAs for athletes' CMJ height PAPE sub−group analysis (baseline−controlled studies).

Group	No. of Studies	Hedges's g	(95% Conf. Interval)	p-Value
		A		
Resistance exercises	22	0.185	0.015 0.355	0.003
Mixed exercises	4	0.163	−0.024 0.549	0.409
Plyometric exercises	3	0.314	−0.117 0.744	0.154
Overall	29	0.196	0.050 0.343	0.009
		B		
Resistance exercises	12	0.235	0.020 0.449	0.032
Mixed exercises	3	0.163	−0.288 0.679	0.429
Plyometric exercises	3	0.61	−0.422 0.544	0.805
Overall	18	0.204	0.030 0.386	0.027
		C		
Resistance exercises	23	0.511	0.306 0.717	<0.001
Plyometric exercises	12	−0.177	−0.335 −0.020	0.027
Overall	35	0.232	0.059 0.405	0.009



(**A**) (**B**) (**C**)

Figure 1. (**A**) presents the bias funnel plot for baseline-controlled, single−arm studies; (**B**) shows the bias funnel plot for non−baseline-controlled studies; and (**C**) displays the bias funnel plot for baseline−controlled studies.

3.4.2. Meta-Analysis Results on Sprint Performance Results

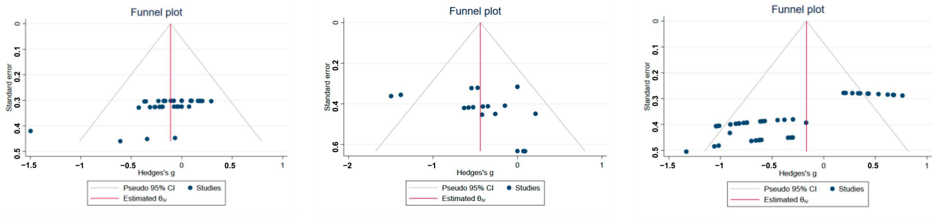
The final inclusion of 26 studies involved 12 studies with 176 participants comparing the acute effects of different CAs on sprint performance. As shown in Supplementary Files S9–S11, the heterogeneity tests for Supplementary Files S9 and S10 indicated no heterogeneity (I^2 = 0% and 30.76%, respectively), leading to the use of a fixed-effects model for the analysis. However, the heterogeneity test for Supplementary File S11 showed high heterogeneity (I^2 = 85.87%), necessitating the use of a random-effects model. The meta-analysis revealed combined effect sizes, indicating that the PAPE from the exercise interventions effectively enhanced sprint performance for the athletes [Hedges's g = −0.11, −0.44, and −0.32; 95%CI: (−0.22, 0.00), (−0.63, −0.25), and (−0.49, −0.13); p = 0.04, <0.001, and <0.001, respectively ($p < 0.05$)].

Subgroup analysis of the CAs was categorized into resistance exercises, plyometric exercises, and mixed exercises. The results from Table 2A–C for subgroup analysis for resistance exercises reported effect sizes indicating that resistance exercises in acute intervention can effectively improve subsequent sprint speed in athletes [p = 0.014, <0.001, and <0.001 ($p < 0.05$)]. However, the plyometric exercises' p = 0.883 and 0.968 ($p > 0.05$), and mixed exercises' p = 0.507 ($p > 0.05$), implying that acute interventions using plyometric or mixed exercises did not affect subsequent sprint speed improvement.

Table 2. (**A**) Different CAs for athletes' sprint time height PAPE sub-group analysis (baseline−controlled, single-arm studies); (**B**) Different CAs for athletes' sprint time PAPE sub-group analysis (non-baseline−controlled studies); (**C**) Different CAs for athletes' sprint time PAPE sub−group analysis (baseline−controlled studies).

Group	No. of Studies	Hedges's *g*	(95% Conf. Interval)	*p*-Value
		A		
Resistance exercises	13	−0.226	−0.406 −0.046	0.014
Mixed exercises	21	−0.046	−0.180 0.089	0.507
Overall	34	−0.111	−0.218 −0.003	0.045
		B		
Resistance exercises	15	−0.475	−0.667 −0.284	<0.001
Plyometric exercises	3	0.054	−0.662 0.770	0.883
Overall	18	−0.440	−0.625 −0.255	0.000
		C		
Resistance exercises	19	−0.714	−0.892 −0.536	<0.001
Plyometric exercises	24	−0.005	−0.246 0.236	0.968
Overall	43	−0.316	−0.504 −0.128	0.001

The funnel plot results indicated asymmetry, as shown in Figure 2A–C. The Egger's test for Figure 2A detected publication bias among the included studies ($p = 0.001 < 0.1$). After applying the trim-and-fill method, the results remained unchanged, suggesting the results are acceptable [Hedges's *g* = −0.111; 95%CI: (−0.218, −0.003)]. No clear publication bias was detected for Figure 2B ($p = 0.22 > 0.1$). The Egger's test for Figure 2C indicated significant publication bias ($p < 0.1$), and the trim-and-fill method adjusted the effect size change. This change necessitates a cautious interpretation of these results [Hedges's *g* = −0.316; 95%CI: (−0.504, −0.128) to Hedges's *g* = −0.131; 95%CI: (−0.318, 0.055)].



(**A**) (**B**) (**C**)

Figure 2. (**A**) presents the bias funnel plot for baseline−controlled, single−arm studies; (**B**) shows the bias funnel plot for non-baseline−controlled studies; and (**C**) displays the bias funnel plot for baseline−controlled studies.

3.4.3. Sensitivity Analysis

To investigate whether the heterogeneity among the various studies was induced by an individual study, sensitivity analysis was executed using Stata 17.0. Subsequent to the sequential exclusion of a single study, no significant fluctuation in effect sizes was observed (refer to Supplementary File S12). This indicates the stability of the results.

4. Discussion

In 1982, Manning and colleagues [43] pioneered the discovery of the "muscle potentiation" theory during their research on rat muscle fibers. The subsequent year, in 1983, Vandervoort and colleagues [44] observed an enhancement effect in the anterior tibialis and plantar flexor muscles after Maximal Voluntary Contractions (MVC) in humans. The concept of PAPE was officially introduced by Brown et al. [45] in 1998. Since its inception, PAPE has garnered significant attention and recognition in both academic research and practical training settings. Professionals have actively sought to leverage the effects of PAPE to enhance training outcomes and optimize competitive performance.

The present study encompassed 26 different experimental studies related to PAPE with three different CAs, involving a total of 378 participants. Through the use of meta-analytic procedures, the PAPE effects of three different CAs were examined: resistance exercises, plyometric exercises, and mixed exercises. Particular attention was paid to athletes' jumping and sprinting abilities. The findings demonstrate that resistance exercises generated a more pronounced PAPE effect in both jumping and sprinting performances compared to the other two methods.

4.1. Post-Activation Performance Enhancement on Jumping Performance through Different Conditioning Activities

The meta-analysis results suggest that the PAPE effects generated by resistance exercises were superior to those produced through plyometric or mixed exercises. The effectiveness of PAPE was found to be highly correlated with the intensity of the inducing stimulus, indicating that greater intensities were more likely to lead to optimal PAPE responses [46]. In the 17 included studies that investigated PAPE impacts on CMJ height, a commonality was the use of stimuli greater than 80% of the one-repetition maximum (1RM). The reason heavy resistance exercise yielded better PAPE outcomes could be attributed to several neuromuscular mechanisms: the quantity and efficiency of neurotransmitter transmission were increased, the synaptic junction excitability was enhanced, the efficacy of the muscle fiber sodium–potassium (Na^+–K^+) pump was improved, the likelihood of successful action potential propagation was increased, and the recruitment efficiency of high-threshold motor units was boosted. Collectively, these mechanisms lead to a substantial enhancement in explosive performance [13].

Plyometric exercises are closely associated with the recruitment of Type II muscle fibers [47], which are the biological foundation necessary for performing Stretch-Shortening Cycle (SSC) movements—a mechanism employed during jumping actions. Hence, in theory, employing plyometric exercises as a CA to induce PAPE could enhance an athlete's jumping performance. However, the results of the present study imply that plyometric exercises do not elicit superior PAPE effects compared to resistance exercises. Possible explanations for such findings include the following. (1) The stimulus intensity of the plyometric exercises may be too low to prompt a significant involvement of fast-twitch muscle fibers in the jump execution process [48]. For instance, studies by Dello et al. applied a constant drop height of 25 cm in depth jump exercises for participants of various athletic abilities without tailoring the drop height to each individual's fitness level [22], suggesting that, for more trained athletes, a 25 cm drop might not be sufficient to induce optimal PAPE. (2) The complexity of plyometric exercises might pose challenges for inexperienced participants to execute correctly. Tobin and colleagues discovered that exercises such as ankle hops, hurdle jumps, and depth jumps were capable of inducing superior PAPE effects [21]. However, in contrast, Dello et al. found that similar plyometric exercises, including bilateral and unilateral depth jumps, did not lead to PAPE in their subjects [22]. The key difference may lie in the participants' proficiency levels: Tobin's [21] subjects were highly trained adult rugby players who could reliably perform the high-intensity phases of 'ground contact buffering' and 'concentric drive' in depth jump exercises, while Dello's [22] subjects were less experienced adolescent athletes who might struggle with the complex movement patterns required for such exercises.

The absence of PAPE following mixed exercises could be attributed to the cumulative effect of the exercise load, which combines resistance exercises with plyometric exercises, potentially leading to an excessive fatigue state [27]. Following plyometric exercise, the body experiences concurrent fatigue and potentiation effects. If the potentiating factors outweigh fatigue, PAPE will gradually develop and reach its peak. In contrast, if fatigue predominates, it will delay the onset of PAPE and diminish its duration of effectiveness [6]. Thus, the timing, peak, and duration of PAPE depend on the balance between the potentiating effects and fatigue [18]. The specific reasons for this are as follows. Performing plyometric exercises immediately after resistance exercises without an appropriate recovery interval may compound fatigue. In such cases, the athlete experiences dominant fatigue after resistance exercises, and the immediate transition to plyometric exercises can exacerbate this fatigue. The accumulation of dual fatigue necessitates an extended recovery period for the body. Further, plyometric exercises impose a high demand on neuromuscular excitability. When fatigue predominates, neuromuscular excitability decreases, resulting in prolonged ground contact times and reduced explosive force during activities like depth jumps. As such, this diminishes the stimulus intensity required for effective PAPE. On the other hand, while several studies integrated a rest interval between resistance and plyometric exercises, with reported rest durations as brief as 3 min, the widely recognized optimal timeframe for PAPE is between 4 and 12 min, indicating that the potentiation effects only start to predominate after the fourth minute. Engaging in plyometric exercises at the third minute clearly falls within the fatigue-dominant period. Thus, when selecting mixed exercises as CAs, it is essential to arrange an appropriate recovery time and manage the relationship between stimulus load and fatigue recovery effectively.

4.2. Post-Activation Performance Enhancement on Sprinting Performance through Different Conditioning Activities

The results of the meta-analysis indicate that the PAPE effects elicited by resistance exercise protocols appear to surpass those of plyometric and mixed exercises. This enhanced efficacy may not only be attributed to the physiological mechanisms discussed earlier but also to the biomechanical patterning of sprinting actions. Current standards for sprinting techniques prioritize the cultivation of "front-side mechanics," which entail lower-limb movements primarily occurring in front of the body. The intention is to bolster the ability of the limbs to execute a "whip-like" downward thrust and a rapid "hip drive." This focus ultimately aims to indirectly elevate the efficiency of force production in the vertical direction during the support phase of sprinting. An array of literature supports the notion that the vertical ground reaction forces exerted during this phase play a crucial role in enhancing speed [49–52]. Athletes striving to achieve this "whip-like" thrust and augmented vertical force production necessarily demand higher lower-limb strength, particularly in the muscles of the posterior chain (such as the gluteus maximus and the hamstrings). When selecting resistance exercises for the CA of PAPE, the back squat and hip thrust are predominantly preferred in most studies. The hip thrust, in particular, proves to be highly effective in activating the muscles of the posterior chain, such as the gluteus maximus and hamstrings [53]. Although the back squat primarily targets the quadriceps, it still activates the gluteus maximus to a certain degree [54]. As such, through the enhanced activation of the posterior chain musculature with resistance exercises, there was an indirect improvement in the vertical ground reaction forces during the running process, which in turn enhanced subsequent sprint performance.

Both plyometric exercises and sprinting rely on the Stretch-Shortening Cycle (SSC) mechanism of the lower-limb muscle groups. Theoretically, plyometric exercises should induce a more potent PAPE effect for sprint performance. Nonetheless, the studies included in the present research did not corroborate this outcome. Possible explanations for this discrepancy are as follows. On the one hand, the inconsistency with the movement plane may be related. The CAs employed in previous research, such as depth jumps, hurdle hops, and tuck jumps, predominantly initiate vertical movement via explosive lower-limb extension, with minimal engagement in forward horizontal movement—essential for linear sprinting. Studies have shown that executing movements in distinct directions necessitates distinct intermuscular and intramuscular coordination mechanisms [55]. Thus, the rapid SSC benefits induced by athletes in the upward direction fail to effectively transfer to the horizontal sprinting motion pattern. On the other hand, the research under review mostly used bilateral actions for CAs, with limited attention to unilateral actions, which are more closely related to the sprinting movement pattern. If unilateral plyometric exercises (such as single-leg hops or bounding) were employed, a more favorable sprint PAPE might be produced.

In the field of sprint performance PAPE methodologies, mixed exercises that integrate resistance with sprint exercises are gaining attention. Examples include utilizing elastic resistance combined with sprinting or incorporating sled resistance sprinting. These exercises blend sprint mechanics with resistance, ensuring that the movement is directed forwards. This approach addresses the vertical motion typically associated with plyometric exercises, which may not directly translate to sprinting mechanics. The designers of these training interventions posit that such hybrid exercises could mimic the same biomechanical properties of short sprints, thereby inducing PAPE [30,56] Despite the initial design intentions, the experimental outcomes have not consistently aligned with expectations. This discrepancy may arise from the fact that, although mixed exercises incorporate sprint mechanics, the inclusion of resistance elements, such as elastic bands or sled friction, often requires sprint actions to be performed at a slower pace. Thus, the type of PAPE elicited tends to focus more on the slow SSC mechanisms of the lower-limb musculature rather than the rapid SSC mechanism essential for sprinting. Moreover, while elastic bands and sleds impart a certain degree of resistance to the body, the intensity of this resistance is substantially less than that of resistance exercises and, hence, does not fully replicate the intrinsic bodily adaptations elicited by resistance exercises.

In summary, resistance exercises demonstrate superior PAPE effects on jump and sprint performances compared to plyometric and mixed exercises. However, the contributions of the latter cannot be entirely discounted, as PAPE outcomes are influenced by various factors. These include the participant's training history, the intensity of the CAs, the motor pattern expression, and the delicate balance between fatigue and potentiation effects. While the studies included may not exhaustively elucidate the diversity of PAPE responses to varied CAs on jump and sprint performances, they do have representative value from a research design perspective. Additionally, post-potentiation interventions exhibited less pronounced changes in short-distance sprint outcomes compared to longer distances (for example, 10 m vs. 30 m). As a result, in the present study, a subgroup analysis was not conducted for sprint distances, potentially introducing biases into the research findings. Therefore, there is a need for further investigation into the PAPE effects on sprints of varying lengths.

4.3. Limitations of This Study

(1) In the present research, 26 articles were compiled, acknowledging variability in factors such as athletes' levels, training environments, and subject conditions, which were not entirely consistent. Additionally, the overall small sample size of participants was acknowledged. This may have led to insufficient argumentation strength. (2) Additionally, due to the lack of detailed descriptions regarding study and blinding designs, several studies lacked accessible endpoint data. (3) A number of studies lacked a control group, and there were endpoints that did not have baseline values, which introduced three sets of data for each endpoint, potentially confounding the outcomes of subgroup analyses. (4) The heterogeneity in the present study can be attributed to several factors: differing CAs (movement patterns and load intensity), participant variances (sport, training level, age, and gender), and disparities in experimental design (warm-up activities, environment, intervention duration, and the measurement tools and methods for the endpoints). (5) The PAPE effect was also constrained by various factors aside from different induction methods, including training background, years of training, specific sports, load magnitude, physiological state, age, and gender. The primary focus of the present study was on analyzing various CAs, and broader perspectives or analyses were not explored.

4.4. Future Research Prospects

(1) To comprehensively explore the impact of different CAs on the PAPE effect, more rigorous experimental designs are warranted. Randomized parallel-control or crossover

trials can provide deeper insights into the acute enhancement effect of various CAs on athletic performance and the duration of this enhanced state. (2) Regarding the selection of outcome measures, in addition to kinetic parameters expressed through actions such as running and jumping, the selection of endpoints could also be considered from the perspective of physiological changes within the body, including alterations in lower-limb muscle–tendon stiffness, pennation angle, muscle activation, and changes in muscle cross-sectional area. (3) Investigating the role and differences of PAPE effects induced by various CAs across different sports, ages, and genders holds the potential to provide valuable evidence-based guidelines for the practical application of PAPE effects.

5. Conclusions

Resistance exercises can have a better effect on athletes' jumping and sprinting performance PAPE, and the effect is better than that of plyometric exercises and mixed exercises. According to the results of this meta-analysis, plyometrics and mixed exercises have little effect on jumping and sprinting PAPE. However, due to the limitations of the number and quality of included studies, the effects of plyometrics and mixed exercises on PAPE cannot be completely negated. The above conclusions need to be verified by more high-quality experimental studies.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/app14209301/s1.

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