



Optimizing Post-activation Performance Enhancement in Athletic Tasks: A Systematic Review with Meta-analysis for Prescription Variables and Research Methods

Kai Xu¹ · Anthony J. Blazevich² · Daniel Boullosa^{3,4,5} · Rodrigo Ramirez-Campillo⁶ · MingYue Yin¹ · YuMing Zhong¹ · YuHang Tian¹ · Mitchell Finlay⁷ · Paul J. Byrne⁸ · Francisco Cuenca-Fernández^{9,10} · Ran Wang¹

Accepted: 13 December 2024
© The Author(s), under exclusive licence to Springer Nature Switzerland AG 2025

Abstract

Background Post-activation performance enhancement (PAPE) has demonstrated efficacy in acutely improving athletic performance. However, its distinction from general warm-up (GW) effects remains ambiguous, and experimental designs adopted in most PAPE studies exhibit important limitations.

Objectives The aims of this work are to (i) examine the effects of research methodology on PAPE outcomes, (ii) explore PAPE outcomes in relation to comparison methods, performance measures, GW comprehensiveness, recovery duration, participants' characteristics, conditioning activity (CA) parameters, and (iii) make recommendations for future PAPE experimental designs on the basis of the results of the meta-analysis.

Methods Four databases were searched for peer-reviewed English-language literature. Risk of bias was assessed using a modified Cochrane Collaboration's tool and PEDro scale. PAPE groups were compared with control groups, pre-conditioning activity (pre-CA) performances were compared with post-conditioning activity (post-CA) performances throughout a verification test in PAPE groups, and control groups were compared before and after the “rest” period using a three-level meta-analysis. Further analyses, including subgroup analysis and both linear and nonlinear meta-regression methods, were used to explore the effect of different moderating factors on PAPE magnitude. A subgroup analysis of GW comprehensiveness was conducted using four classification methods. One method classified GW as non-comprehensive (stretching or jogging only), partially comprehensive (stretching, jogging, and low-intensity self-weighted dynamic exercises), and comprehensive (adding maximal or near-maximal intensity CAs to a partially comprehensive GW). The other three classifications were adjusted according to the type and number of GW exercises. Certainty of evidence was assessed using the GRADE approach.

Results The final analysis included 62 PAPE studies (1039 participants, male: $n = 857$, female: $n = 182$) with a high risk of bias and low certainty of pooled evidence. A trivial PAPE effect was observed from pre- to post-CA (effect size [ES] = 0.12, 95% CI [0.06 to 0.19], prediction intervals [PI] = -0.29 to 0.54); a small PAPE effect was observed when compared with a control group (ES = 0.30, 95% CI [0.20 to 0.40], PI [-0.38 to 0.97]). The slightly greater effect against control resulted from a small decrease in performance in control groups (ES = -0.08, 95% CI [-0.13 to -0.03], PI [-0.30 to 0.14]), but there was no relationship with between PAPE recovery time ($\beta = -0.005$, $p = 0.149$). Subgroup analyses showed that PAPE magnitude was greater for non-comprehensive GWs (ES = 0.16) than comprehensive (ES = 0.01) and partially comprehensive GWs (ES = 0.11). In contrast, the control group showed a decline in performance after comprehensive GW (ES = -0.20). An inverted U-shaped PAPE was noted as a function of recovery time. In some cases, PAPE appeared to manifest at < 1 min post CA. Additionally, participants with longer training experience (ES = 0.36) and higher training levels (ES = 0.38) had larger PAPE magnitudes. PAPE effect was higher in females (ES = 0.51) than males (ES = 0.32) and mixed groups (ES = 0.16) but did not reach a significant difference ($p > 0.05$). Plyometric exercise (ES = 0.42) induced greater PAPE amplitude than traditional resistance exercise (ES = 0.23), maximal isometric voluntary contraction (ES = 0.31) and other CA types (ES = 0.24).

Conclusions Although the overall pooled results for both PAPE pre- versus post-CA and PAPE versus control group comparisons showed significant improvement, the wider and past-zero prediction intervals indicate that future studies are still likely to produce negative results. The comprehensiveness of the GW, the time between GW and the pre-CA test, participant

Extended author information available on the last page of the article

sex, training level, training experience, type of CA, number of CA sets, and recovery time after CA all influence the PAPE magnitude. The PAPE magnitude was trivial after comprehensive GW, but it was greater in studies with a control group (i.e., no CA) because performance decreased over the control period, inflating the PAPE effect. Finally, two theoretical models of PAPE experimental design and suggestions for methodological issues are subsequently presented. Future studies can build on this to further explore the effects of PAPE.

Protocol Registration The original protocol was prospectively registered (osf.io/v7sbt) with the Open Science Framework.

Key Points

A post-activation performance enhancement (PAPE) effect was observed in jump, sprint, agility, and upper-body performances when compared with control groups.

PAPE effects are trivial when conditioning activities (CAs) are performed after comprehensive general warm-up (GW), including test-specific exercises (i.e., test practice).

PAPE showed an inverted U-shaped trend with recovery time after CA. The optimal recovery time point was ~5.5 min, with statistically significant recovery intervals of 4.5–6.3 min for jumping, 3.6–8.6 min for sprinting, and 3.6–11.0 min for upper body performance. When compared with a control group, the interval range was extended.

Of all the CA types, performing three sets of five repetitions each of plyometric exercise was sufficient to induce a significant PAPE effect.

Current PAPE experimental designs were unable to distinguish the effect of GWs on PAPE magnitudes, and incomplete reporting of randomization methods, blinding, familiarization experiments, a priori sample estimation, cumulative effect, and measurement reliability metrics are concerns.

Performance enhancement is strongly influenced by both temperature-related and non-temperature-related vascular, cellular, and neuromuscular mechanisms, including increases in nerve conduction velocity, anaerobic energy provision, and muscle metabolism (and thus shifts in the force–velocity relationship) as well as enhanced oxygen uptake kinetics, psychological readiness, muscle blood flow, and post-activation potentiation (PAP) [2, 5]. Independent of the involved mechanisms, the term post-activation performance enhancement (PAPE) has been proposed to describe the acute enhancement of athletic performance (e.g., higher jump height) after warm-up, most commonly occurring after completion of maximal or near-maximal intensity CAs (e.g., squat, power clean, jump, and sled towing) [7–10]. Classically, the short-term performance enhancements obtained after brief bouts of maximal activities were ascribed to PAP, a muscle-memory mechanism originating from myosin phosphorylation that heightens muscle responsiveness during muscle twitch contractions [11, 12]. However, this effect is involuntary and short-lived (~28 s), and triggered only by localized maximal contractile history [9, 10]. As a result, PAP may have minimal or no effect on performance in most tasks.

Although PAPE is influenced by numerous factors, its magnitude is assumed to be related to the balance between performance enhancement factors and fatigue [7, 13–15]. Specifically, when enhancement effect exceeds fatigue, athletic performance is enhanced, and vice versa [13, 15]. In their classic review, Tillin and Bishop [15] proposed a theoretical model of CA volume and recovery time to explain the balance between enhancement and fatigue (they used the term PAP rather than the more recently suggested term PAPE). They suggested that athletic performance improved in the immediate post-CA period when its volume was low but would take longer to manifest, following an inverted U-shape, when volume was high [15]. While this model does not include other factors that might influence the time course of enhancement, such as motor pattern perseveration (i.e., motor pattern interference) effects [16–18], it provides a useful model for application.

Furthermore, the effect of PAPE is contingent on factors such as the CA type, duration, and intensity [7, 19].

1 Introduction

The warm-up is a common procedure in training and competition [1–3] and may include a number of different exercises (and their combinations) as low-intensity aerobic exercises, static and dynamic stretching, dynamic bodyweight exercises, and conditioning activities (CAs) or sport-specific exercises [1, 2, 4–6]. All these procedures aim to achieve an acute improvement in athletic performance [1, 3, 5].

Traditionally, the CA intensity (~ 80% repetition maximum [RM]), has been regarded as a crucial modulating factor eliciting potentiation responses owing to its efficacy in stimulating type II fibers (i.e., fast fibers) [15, 20, 21]. Additionally, neural factors such as increased motor unit recruitment, motor neuron excitability, and conduction velocity of muscle fibers are also considered synergistic contributors to generating PAPE [9, 22]. In this regard, it must be noted that acute bouts of localized exercise foster neuroplasticity in particular regions of the primary motor cortex, augmenting corticospinal excitability and rendering specific-related motor neurons more responsive to nerve impulses [23]. Thus, along with the nonlocalized neurogenic effect, CAs with similar movement patterns and sufficient dynamic activity may significantly enhance central motor output, ultimately leading to improved athletic performance [24]. However, factors such as sex, strength level, training experience, and selected testing protocol may additionally influence the balance of enhancement and fatigue and, thus, overall PAPE magnitude [7, 20, 21, 25, 26].

Currently, the optimal CA parameters to maximize PAPE have not been completely elucidated [8, 27, 28]. Interindividual variabilities in responses to CAs [8, 29, 30] and deficiencies in experimental design [31–33] have hindered the search for optimal CAs. In this regard, it has also been suggested that power-trained athletes may benefit more from brief, high-intensity CAs while endurance athletes may benefit more from longer, low-intensity CAs, following a principle of specificity [34]. Therefore,

identification of all the factors related to an optimal CA is warranted.

The experimental protocol used in PAPE studies typically follows the sequence:

General warm-up (GW) → Rest-1 → Pre-CA Test → Rest-2 → CA or control → Rest-3 → Post-CA Tests (i.e., verification tests) (Fig. 1) [9, 15, 28, 35].

This protocol aims to determine the acute PAPE effect through comparison of post-CA to pre-CA test performances, with multiple post-CA tests performed to ensure that performance changes are detected regardless of the time point(s) at which they might appear. However, if the experimental protocol does not include a control test (or a separate control group/condition) after Rest-2 (Fig. 1), and therefore it is assumed that GW has minimal effect on subsequent test performances, this could introduce a critical bias [9]. Indeed, Blazevich and Babault [9] indicated that the GW to CA recovery time is rarely considered in PAPE studies. Therefore, GW characteristics and recovery durations (or strategies) [1, 2, 5, 6] used before the pre-CA test may introduce bias in experimental designs [9, 28, 35], particularly when a control condition is not included for comparison against the CA condition after Rest-2 (Fig. 1).

Partly as a consequence of study limitations, Vasconcelos et al. [36] and Singh et al. [37] rated the certainty of evidence for the results for endurance performance and change of direction performance in PAPE studies as very low and low, respectively. Other researchers have also highlighted methodological design issues in PAPE studies, including lack of condition randomization, participant and tester blinding, and protocol familiarization

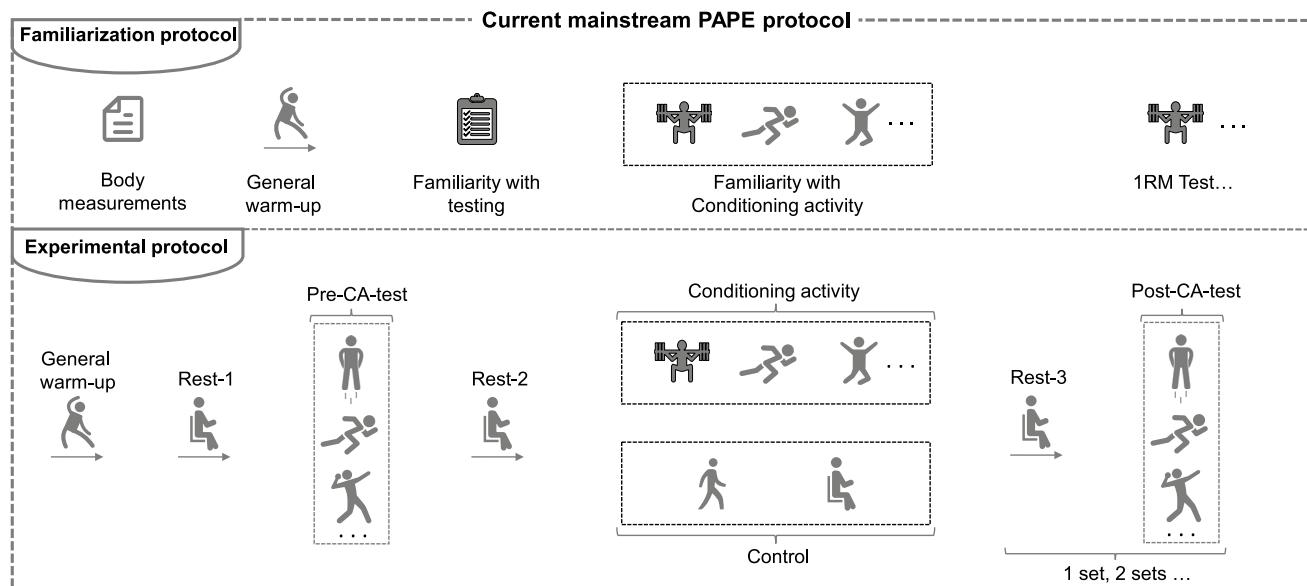


Fig. 1 Inclusion criteria for the PAPE protocol, using the back squat as an example. CA conditioning activity, RM repetition maximum, Rest-1 time from general warm-up (GW) to pre-CA testing, Rest-2 time from pre-CA testing to CA, Rest-3 time from CA to post-performance testing

as well as measurement reliability issues and lack of a priori sample size estimation [9, 28, 35]. Additionally, the inclusion of multiple post-CA tests (over time) is common in PAPE studies, which may introduce bias through post-activation potentiation (e.g., through stimuli summation), learning effects (additional test practice), further temperature increases (amongst other physiological changes), or fatigue (e.g., insufficient interest recovery) [13, 15]. Further, most meta-analyses have included studies without control groups or conditions, thus only using within-group, pre- to post-CA comparisons [7, 20, 38, 39], potentially biasing the results toward significant effects [40]. Nonetheless, in recent years, numerous published studies have incorporated more robust methodological designs with the inclusion of control groups or conditions [41–54]. A comprehensive, updated systematic review with meta-analysis, including between-group or condition comparisons, may therefore advance our understanding of PAPE. Although several previous systematic reviews [36, 37, 55] have included between-group or condition comparisons, their narrow focus (e.g., agility-only PAPE [37] or bodyweight-only CA [55]) precludes a more comprehensive understanding of all the PAPE effects within GW protocols.

Given the above, we have analyzed the PAPE effect through an updated systematic review of the literature with meta-analyses for critical experimental design factors. Our specific aims included: (i) the evaluation and progressive analysis of the effect of research methodology (e.g., randomization, repeated post-CA testing effects) and (ii) quantification of PAPE magnitudes in studies using different comparison methods (e.g., between-group or condition versus within-group or condition), participants' characteristics (e.g., sex, training level, training experience), CA parameters (types, number of sets), outcome measures (e.g., throw, jump, sprint), GW comprehensiveness (e.g., with test-specific exercises versus without test-specific exercises), and recovery durations (e.g., at Rest-1, Rest-2, Rest-3). Subsequently, we make recommendations for future experimental designs based on the meta-analytic results.

2 Methods

2.1 Registration of Systematic Review Protocol

The systematic review followed the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) 2020 guidelines [56]. Study titles have been registered in the Open Science Framework (osf.io/v7sbt). The protocol registration took place after the completion of data analysis

and chart preparation but before the secondary search and re-analysis.

2.2 Search Strategy

Prior to the formal search, one of the authors (K.X.) conducted an abbreviated search for “postactivation” in the PubMed retrieval system, reviewing articles individually from 1998 to 16 December 2023. All potentially eligible studies for PAPE topics were included in Endnote (version 20; Clarivate Analytics, Philadelphia, PA, USA) through manual searching. The Word Frequency Analyzer tool (<http://sraccelerator.com/#/help/wordfreq>) was employed to count the high-frequency keywords included in the studies. Subsequently, a search strategy was developed on the basis of “terms commonly used in PAPE studies” AND “interventions commonly used” AND “performance measures commonly used”. The search terms were formulated to encompass as much of the manually retrieved literature as possible. Searches for title/abstract were conducted on 16 December 2023, in the following databases: Web of Science, PubMed, Scopus, and SPORTDiscus (see the Electronic Supplementary Material (ESM) for specific search details). Additionally, this work sought studies meeting the criteria by identifying published reviews of PAPE studies, utilizing Google Scholar, and examining citations of included studies. The initial search retrieved only peer-reviewed English-language journal studies, and the second search included recent studies subsequent to the first search that also included peer-reviewed non-English language journal studies. The most recent retrieval was conducted on 5 March 2024.

2.3 Study Selection and Eligibility Criteria

One author (K.X.) performed the identification and screening of the literature, and during the eligibility phase, two authors (K.X. and Y.M.Y.) reviewed the full texts on the basis of exclusion and inclusion criteria. In cases where individuals were unable to determine whether a study should be excluded or not, the decision was made in consultation with a third author (R.W.). All processes were conducted using Endnote 20. The eligibility criteria for articles are available in Table 1.

2.4 Data Extraction

Data extraction was independently conducted by two authors (K.X. and Y.M.Y.), and the extracted data were reviewed and validated by another two authors (Y.M.Z. and R.W.). Data were extracted from the included studies and organized into Excel® tables (Microsoft Corporation, Redmond, WA, USA) as follows: (1) study design and basic information; (2) participants' characteristics, training level, and training

Table 1 Eligibility criteria for systematic review

Inclusion criteria

- P Healthy individuals, with no age restrictions
 I Involved various forms of conditioning activities (CA) that entail near-maximum or maximum intensity
 C No form of CAs, such as sitting or walking
 O Measurements that showed athletic performance (e.g., jump, sprint, agility, throw)
 S Randomized controlled, parallel and crossover trials. The PAPE protocol aligned with that shown in Fig. 1

Exclusion criteria

1. The study had both a pre-CA test and a control group. The tests were administered on the same day
2. The control group and the PAPE group shared the same pre-CA test
3. Re-warm-ups and priming studies that involved only recovery times of < 1 min or > 30 min
4. Rest-1, Rest-2, Rest-3 time (Fig. 1), and control group only involved sitting or walking
5. Physiology, psychology, and other tests that did not reflect athletic performance
6. CA involved whole body vibration training, isokinetic training, electrical stimulation and supplements
7. CA process performed low intensity and stretching exercises. Number of CA sets > 4
8. Grey literature and non-randomized studies
9. Modified PEDro scale < 16 and studies with missing data

experience; (3) conducting the GW training content, Rest-1, and Rest-2; (4) type of CA, volume, and intensity; (5) recovery time in the CA group (Rest-3) and duration from post-GW to post-performance test in the control group; and (6) methods of performance testing and outcome measurements, including means and standard deviations (SD) of pre- and post-CA tests in the PAPE and control groups. For outcome measurements presented as pictures, data were extracted using the WebPlotDigitizer tool (version 4.5; <https://apps.automeris.io/wpd/>, $r=0.99$, $p<0.001$) [57]. A total of 13 studies used the picture extraction tool [29, 45, 58–68]. In cases where data were missing, the corresponding author of the study was contacted to request the information. After the initial email, if there was no response, a follow-up email was sent after a 48-h interval. If there still was no response after 2 days, the study was not included.

2.5 Coding of Studies

Since few PAPE studies presented details of the GW, we were only able to determine the comprehensiveness of the GW by means of subjective consensual evaluation. Evaluation 1 used a categorization strategy according to RAMP: R = Raise, A = Activate, M = Mobilize, P = Potentiate [4], where “Non-comprehensive” included only two RAMP processes (e.g., RA [58] or RP [69]), “Partially comprehensive” included three RAMP processes (e.g., RAM [70] or RAP [63]), and “Comprehensive” included all four RAMP processes, as demonstrated in the warm-up performed by Abade et al. [41]. It is important to note that “potentiation” (i.e., CA) exercises (including test-specific exercises) may have produced greater neuromuscular stimulation [1, 2, 4, 15], whereas RA and RP were considered

to be equally comprehensive. Therefore, evaluation 2 built on evaluation 1 by considering the non-comprehensive GW with “potentiation” exercises as a partially comprehensive warm-up. For an example, consider Brandenburg et al. [69] (GW is 5 min cycling and two sets of 10 reps of 40–50% 1RM bench press) as a partially comprehensive GW. Evaluation 3 was determined by the presence or absence of potentiation exercises in the GW. If potentiation exercises were incorporated into the GW, as in the study by Chaouachi et al. [71], then it was categorized as “yes”; otherwise, as exemplified by French et al. [58], it was categorized as “no”. Evaluation 4 was based on the presence or absence of test-specific warm-up exercises in the GW. The categorization here resembles evaluation 3, with the distinction that significant movement similarity to the performance testing is required for potentiation exercises. A detailed explanation of the GW evaluation is given in Table 2. It was considered possible that the present authors may have had a subjective bias in their evaluations of GW [72]. Therefore, the evaluation was performed by the first author (K.X.) as well as four external evaluators who were not involved in the study, with the first author writing the methodology and evaluation details in an Excel® sheet and sharing the sheet with the four evaluators via another author (Y.M.Y., i.e., without contact with the reviewers). The four evaluators conducted their evaluation in a blinded manner. Consistency of the evaluation results was calculated by the intraclass correlation coefficient (ICC) [73], and the mean value of the overall evaluation was above 0.80. Finally, after discussions, the GW evaluation results were agreed upon (see Supplement 4 in the ESM).

Other categorizations of studies are as follows:

Table 2 Specific interpretation of GW evaluation

Evaluation 1: GW comprehensiveness according to RAMP	Non-comprehensive Partially comprehensive Comprehensive	GW included up to two elements of RAMP, e.g., RA, RP, R, P GW included three elements of RAMP, e.g., RAM, RAP, RMP Included all elements of RAMP. Two studies that did not include all elements of RAMP but conducted too much GW. In this study, we also considered these two studies as complete RAMP warm-ups
Evaluation 2: Is GW likely to improve athletic performance?	Unlikely Possibly Extremely	Studies with P in GW were excluded on the basis of evaluation 1 low. For example, a low intensity RP in evaluation 1 was possibly in evaluation 2, even if there was only one P Based on evaluation 1, “medium,” plus a study of the presence of P in “low” in evaluation 1 Consistent with “high” in evaluation 1
Evaluation 3: Does GW have potentiation exercises?	No Yes	No potentiation exercises Potentiation exercises included explosive bodyweight-based exercises such as jumping and sprinting. Equipment-based weight-bearing exercises such as squats and deadlift
Evaluation 4: Does GW have specialized exercises?	No Yes	No potentiation exercises Specialized exercises were more rigorous than potentiation exercises and require the exercise to have a biomechanical similarity to the movement being tested. For example, sprinting at 80% intensity, or jumping exercises at 80% intensity

GW general warm-up, *R* primarily consists of low-intensity aerobic exercises, such as jogging and cycling, *A* primarily consists of stretching exercises, including dynamic or static stretches, *M* primarily consists of low-intensity self-weighted, dynamic exercises such as self-weighted squats, lunges, and joint mobilization, *P* primarily consists of maximal or near-maximal intensity weight training or explosive training with self-imposed weights, e.g., weighted squats, sprint, and plyometric training

- (1) Rest-1: categorized as short (<4 min), moderate (4–10 min), and long (≥ 10 min). This time point was chosen because phosphagen was close to complete recovery at 4 min [74], and performance tends to decrease when the recovery exceeds 10 min [1, 6, 75].
- (2) Outcome measurements: test indicators were categorized according to those used by Seitz et al. [7] and commonly employed in PAPE studies. These indicators included upper extremity performance, jumping performance, and sprint and agility performances.
- (3) Cumulative effect: the best measurement from the control group’s post-CA tests was selected for comparison with the pre-CA tests. This selection was made because the control group did not perform CA, and the chosen test value could provide a better proxy of the participants’ athletic performance. A significantly higher best value at post-CA testing than pre-CA testing was accepted as indicative of a cumulative effect (enhancement of athletic performance resulting from multiple testing).
- (4) Comparison format: a total of three comparisons were performed, including PAPE versus control condition (between-group), pre- versus post-CA (within-group),

and pre- versus post-control (within-group) comparisons. The outcomes of these three comparisons were analyzed to explore the role of the control group in PAPE studies as well as the differences between within-group and between-group comparisons. Data coding was independently performed by three authors (K.X., Y.M.Y., and Y.M.Z.). Any coding differences were carefully examined and resolved by the investigators before the final analysis.

- (5) Participants’ characteristics: participant sex was categorized into three groups: “male,” “female,” and “mixed”; the level of training was categorized into three groups on the basis of McKay et al.’s [76] classification of athletes “tier 1 physically active,” “tier 2 trained,” and “tier 3 highly trained.” Training experience was categorized into: “< 2 years,” “ ≥ 2 years,” and “unclear.” Because 85.5% of studies did not report both resistance training and exercise training experience for participants, and 56.5% of studies reported only a minimal training threshold (e.g., at least 1 year of resistance training), resistance training experience was prioritized when resistance training was the CA in the original study. In other cases, exercise training experience was pri-

- oritized. If the study did not specify the exact years of training experience, a minimum training threshold was used (e.g., if the original study described participants as having engaged in resistance training for at least 1 year, this was recorded as 1 year).
- (6) CA parameters: On the basis of the classification of CAs by Seitz et al. [7] and Wilson et al. [20], we categorized CAs into four types: (1) traditional resistance exercises, involving externally loaded machines such as back squats, deadlifts, and power cleans; (2) plyometric exercises, utilizing one's own body mass and including stretch–shortening cycle exercises such as countermovement jumps, drop jumps, and weighted squat jumps; (3) maximum voluntary isometric contractions, involving isometric contractions in maximal or submaximal forms, such as isometric mid-thigh pulls and isometric back squats; (4) other exercise methods, such as resisted sprint exercises, back squats combined with blood flow restriction and punching with a resistance elastic band. Additionally, the number of CA sets was categorized into “single” and “multiple.”

2.6 Quality Evaluation and Risk of Bias Evaluation

Risk of bias was assessed using a modified version of the Cochrane Collaboration tool [77]. Allocation concealment and blinding of implementers are challenging in PAPE studies, so these two aspects were excluded, and four evaluation criteria were added: familiarization of tests, cumulative effect, measurement bias, and sample size bias. Specifically, to study familiarization effects, studies were categorized as “low risk” if participants completed two or more familiarization sessions, “unclear risk” if they conducted one familiarization session, and “high risk” if none were conducted. To study cumulative effects, studies were categorized as “low risk” if only one post-CA test (i.e., one time point) was conducted (e.g., French et al. [58]), “unclear risk” if two or more post-CA tests were conducted across a time interval of at least 4 min or if multiple tests were conducted simultaneously (e.g., Iacono et al. [78]), or “high-risk” if two or more post-CA tests were conducted with an intertest interval <4 min (e.g., Zimmermann et al. [79]). Again, this categorization was established in accordance with the time required for phosphocreatine recovery. To study measurement bias, studies were considered “low risk” if two or more measurement reliability statistics were reported, e.g., ICC and coefficient of variation (CV), “unclear risk” if only one statistic was reported, and “high risk” if no reliability statistics were reported. Finally, sample size bias was examined by categorizing studies as “low risk” if a priori sample size estimation was correctly described (accurately distinguish between effect size [ES] estimates in *t*-tests and ES estimates in *F*-tests), “unclear risk” if a procedure was

not reported, or “high risk” if a procedure was not reported and the sample size was <10 participants or if ESs were estimated incorrectly.

Study quality evaluation was conducted using the Brughelli et al. [80] modified PEDro scale assessment, which is used to evaluate the completeness of the research methodology process and reporting. This assessment determined whether: (1) inclusion criteria were clearly stated, (2) participants were randomly allocated to groups, (3) interventions were clearly defined, (4) groups were tested for similarity at baseline, (5) a control condition was included, (6) outcome variables were clearly defined, (7) assessments were practically useful, (8) intervention duration was practically useful, (9) between-group statistical analyses were appropriate, and (10) point measures of variability were provided. This scale includes a 10-item scale (range 0–20), and the score for each criterion was as follows: 0 = clearly no; 1 = maybe; and 2 = clearly yes. The discussion of the modified Cochrane Collaboration tool and modified PEDro was initially conducted by three authors (K.X., Y.M.Y., and Y.M.Z.). Evaluations were then carried out independently using uniform criteria that had been agreed upon, and any discrepancies after evaluation were resolved through discussion.

2.7 Statistical Analysis

2.7.1 Data Synthesis and Effect Measures

In this study, two types of comparisons were performed: between-group comparisons between the PAPE and control groups, and pre- and post-CA test comparisons within the PAPE group only. For the former, the mean change (M_{change}) and standard deviation of the change (SD_{change}) were calculated using the following formulae [81–83]:

$$M_{\text{change}} = M_{\text{post}} - M_{\text{pre}} \quad (1)$$

$$SD_{\text{change}} = \sqrt{SD_{\text{pre}}^2 + SD_{\text{post}}^2 - (2 \times r \times SD_{\text{pre}} \times SD_{\text{post}})} \quad (2)$$

where M_{post} and M_{pre} are the mean values of the post- and pre-CA performance tests in the PAPE group or control group, SD_{pre} and SD_{post} are the standard deviations of the post- and pre-CA performance tests in the PAPE or control group, and r is the correlation coefficient. Correlation coefficients for pre and post-CA tests were rarely reported in the included studies and were generally based on the Cochrane Handbook, which conservatively assumes an r of 0.50 [84]. However, the correlation coefficients calculated for the raw data ranged from 0.80 to 0.99 [71, 85]. Owing to the limited amount of raw data, it was not possible to show the correlation coefficients of all studies. Therefore, we adopted

0.80 as the correlation coefficient for the combined analysis and 0.60, 0.70, and 0.90 for sensitivity analyses to assess the stability of the analysis results [36]. Given the typically small sample sizes in PAPE studies, Hedges and Olkin's g -corrected ESs were used [73]. The ES was also employed when making pre- and post-CA test performance comparisons in the PAPE group or condition [82], using the following formula:

$$\text{ES} = \frac{(M_{\text{post}} - M_{\text{pre}})}{\text{SD}_{\text{pooled}}} \times \left(1 - \frac{3}{4(n_1 + n_2 - 2) - 1} \right), \quad (3)$$

where M_{post} and M_{pre} are the means of the pre- and post-CA test performances of the PAPE or control group or condition, n_1 and n_2 are the sample sizes of the pre- and post-CA test performances of the PAPE or control group or condition, and $\text{SD}_{\text{pooled}}$ is the pooled standard deviation of the measurements [73]. In the between-group comparison, M_{post} and M_{pre} represent the mean change between the PAPE group and the control group, respectively, and n_1 and n_2 represent the sample sizes of the PAPE group and the control group, respectively. The specific formulae are as follows:

$$\text{SD}_{\text{pooled}} = \sqrt{\frac{((n_1 - 1) \times \text{SD}_1^2 + (n_2 - 1) \times \text{SD}_2^2)}{(n_1 + n_2 - 2)}}, \quad (4)$$

where n_1 and n_2 are the sample sizes of the PAPE or control groups or conditions at pre- and post-CA testing, and SD_1 and SD_2 are the standard deviations of the tests.

When standard errors (SE) were presented in studies, SD was calculated using: $\text{SD} = \text{SE} \times \sqrt{N}$. ESs of <0.2, 0.2–0.49, and 0.5–0.8 were categorized as small, moderate, and large, respectively [86]. Heterogeneity was evaluated using I^2 and Q tests as the evaluation criteria, with I^2 of 25, 50, and 75% indicating low, moderate, and high heterogeneity, respectively. The Q test was considered significant at $p < 0.1$. Prediction intervals (PI) were calculated to more comprehensively reflect the potential variability of similar studies in the future [87, 88]. The results for sprint and agility tests were multiplied by –1 to calculate the final effect size in the outcome study, and the improvement in effect size was adjusted to reflect a positive enhancement.

2.7.2 Three-Level Meta-analysis

PAPE studies typically reported multiple CAs [44, 89], various measures (e.g., jumping, sprinting, and agility) [41, 48], and performance assessments at multiple time points simultaneously [47–50]. Different ESs in a single study were correlated, and simultaneous inclusion violates the assumption of independence of effect sizes between studies in traditional meta-analyses, potentially leading to an exaggeration of the results [40, 88]. Conversely, if only one effect size or the

average of effect sizes was included, the approach might be too conservative to accurately reflect the true peak value [32, 90]. Therefore, we employed a three-level meta-analysis following the methods of Assink et al. [91], with analysis carried out using the open-source *R* code by Jukic et al. [92], to account for dependence between effect sizes [88, 91]. Multiple measurements and comparisons from the same study were nested within studies, so the variance of the observed effect sizes was decomposed into sampling variance, within-study variance (level 2), and between-study variance (level 3) to account for within-study (or within-group) correlations [93, 94]. Three-level meta-analyses took into account the hierarchical nature of the data (e.g., the effect sizes nested within the studies) so that the extraction of multiple effects from each study retained information, thereby improving the statistical power and providing a more realistic representation of PAPE effect sizes [73, 91].

The model parameters were estimated using the restricted maximum-likelihood (REML) method, and the calculations were cross-verified with the maximum likelihood (ML) method to ensure result stability. Tests of individual coefficients in all models, and their corresponding confidence intervals (CI), were based on a *t*-distribution [92]. Three-level meta-analyses were conducted using the *metafor* package in *R* (version 4.3.0; R Core Team, Vienna, Austria) [95]. Given that PAPE is influenced by recovery time (Rest-3), athletic performance typically declines immediately after completing CA [13, 15]. PAPE meta-analyses often consider the best performance measure value at multiple time points [27, 28] or the average effect size over time [37]. In this study, the 3–12-min time frame was selected for three-level meta-analysis, reflecting the real effect size of PAPE. If a study's performance measurement time point fell outside the 3–12-min interval, the best value from that time point was chosen, for example, French et al. [58] with a Rest-3 time of ~15 s and Guggenheimer et al. [96] with a Rest-3 time of 1 min.

2.7.3 Subgroup Analysis and Meta-regression

Subgroup analyses were conducted on GW comprehensiveness, Rest-1 time, outcome magnitudes, cumulative effects, and comparison format. Additionally, further exploration of the combined, main, interaction, and simple effects of GW comprehensiveness with Rest-1 time was undertaken [95]. This is the functionality provided by the *metafor* package to better explore the role of different factors (https://www.metafor-project.org/doku.php/tips:multiple_factors_interactions). Furthermore, the linear and nonlinear relationships of different variables with PAPE amplitude were explored. This included the relationships between PAPE amplitude and Rest-1 (0–15 min), Rest-2 (0–15 min), and Rest-3 (0–30 min) for various comparison methods. The

relationship between PAPE amplitude and Rest-3 was also examined under different outcome variables (jump, sprint, upper-body, and agility tests). Additionally, PAPE studies with performance improvements within 1 min of Rest-3 time were separately extracted for fitting. This was done to test the validity of the theoretical model of Tillin and Bishop [15]. Finally, the relationship between the percent 1-RM used in traditional resistance exercises as CAs (taking the maximum value from each CA), the total number of plyometric exercise repetitions (calculated as the number of sets \times repetitions), the total duration of isometric contractions (number of sets \times set duration), and the PAPE magnitude in the context of PAPE versus control group were also explored.

All models were compared using linear and various non-linear meta-regressions, including simple linear, cubic polynomial, restricted cubic spline, natural cubic spline, and thin plate spline models [97]. The fitting model was then selected on the basis of the goodness-of-fit parameter and practical considerations [98], since partially linear models, although having a better fit (e.g., lower Akaike information criterion), predicted an increase in PAPE with increasing Rest-3 time. From a practical point of view, this prediction was implausible. Therefore, in this case, the nonlinear model with the best goodness of fit was used. Additionally, for results from the nonlinear model showing a clear inverted U trend, we extracted the minimum significant points (where the first and last 95% confidence limits' upper and lower bounds in the fit profile were greater than 0) and the maximum points (the maximum value of the effect size in the fit profile). This was done because the fit models allowed for more accurate predictions of the future effects of different variables on the PAPE magnitude [99]. Restricted cubic spline demonstrated the best goodness of fit among all the nonlinear models in this study. Furthermore, for the variables Rest-1 time and Rest-2 time, the *loess* model for nonlinear fitting was used [100] because this model was more sensitive to the distribution of the original data, which allowed for a better characterization of the overall trends between the different study effect sizes [100]. All regression models were performed using the *metafor* package and later visualized with the *ggplot2* package [101].

2.7.4 Publication Bias and Sensitivity Analysis

Risk of publication bias was assessed using funnel plots [102] combined with Egger's test [103], where $p > 0.05$ indicated no risk of publication bias. The examination of publication bias was conducted separately within (level 2) and between (level 3) studies. Funnel plots and Egger's regression tests are mainly used to determine whether the overall effect size is symmetrical by subjective or quantitative means, and thus whether the included studies are at risk

of publication bias [104]. However, this study was analyzed using three-level meta-analysis, which typically incorporates multiple effect sizes in a single PAPE study. These effect sizes were in turn influenced by Rest-3 time, and the effect sizes of individual PAPE studies themselves varied. Therefore, this study examined the risk of publication bias at level 2 (within-study) and level 3 (between-study, average of individual study effect sizes) for different comparison methods. A three-level meta-analysis was performed to evaluate the superiority of the model compared with traditional meta-analyses. Subsequently, Hat [105], Cook's distance [105], and studentized residuals [106] were employed for leverage, outliers, and influential case diagnosis within-study (level 2) and between-study (level 3), respectively. Cases were red flagged when their hat and Cook's distance values were greater than three times their respective mean, and with a Studentized residual's value greater than 3, in absolute values. The three-level meta-analysis was then repeated after excluding outliers to assess the stability of the model. Additionally, each study was individually excluded within (level 2) and between (level 3) studies to determine the impact of each study on the overall results [88].

As a sensitivity analysis, we used cluster-robust variance estimation methods [107] with small-sample adjustments [108] to adjust the within-study standard errors for correlations between effect sizes. We set the correlation at 0.6 and also analyzed values of 0.4 and 0.8. If the results changed significantly, we applied these methods; otherwise, we retained the original model.

2.7.5 Certainty Assessment

Evidence of validity for each study was amalgamated with quality scores to facilitate result discussions. The Grading of Recommendations Assessment, Development, and Evaluation (GRADE) methodology was employed to assess the level of evidence [109, 110], ranging from very low to high levels of certainty. The GRADE approach evaluates certainty of findings in five domains, including risk of bias, inconsistency of results, indirectness of evidence, imprecision, and publication bias. GRADE assessments were conducted by two authors (K.X. and Y.-M.Y.) and subsequently reviewed by a third author (R.W.).

3 Results

3.1 Search Results

Initially, 15,681 studies were retrieved, which was reduced to 7227 after removal of duplicates. A total of 695 potential full texts were identified after abstract/title screening, and a final review of the full texts identified 62 studies that

met the inclusion criteria. Additionally, a separate search for non-English peer-reviewed studies was conducted and ultimately no eligible studies were found (see Supplement 7 in the ESM). Four studies were included after a secondary search, and two studies were included after a third search. Of the 68 studies that met the inclusion criteria, three studies had PEDro scores < 16 [111–113] and were therefore excluded. Additionally, three studies with missing data [114–116] were excluded after unsuccessful attempts to contact the authors. Authors of other studies with missing data returned the required information after contact [52, 71, 85, 117, 118]. Therefore, a total of 62 studies [29, 31, 33, 41–54, 58–71, 78, 79, 85, 89, 96, 117–142] were finally included in the study for quantitative analysis (Fig. 2).

3.2 Study Characteristics

A summary of participants' characteristics and analyses of the studies included in the meta-analysis is presented in Table S1 and S2 (see Supplement 5 and 6 in the ESM). Of the 62 included studies, 56 were randomized crossover studies and 6 were randomized parallel studies. The total number of participants in these studies was 1039 (857 males and 182 females), aged between 15 and 35 years.

Sixteen studies had < 2 years of training experience, eight were unclear, and the others had ≥ 2 years of training experience. Twelve used maximal voluntary isometric contractions, 18 utilized plyometric exercise, 36 involved traditional resistance exercise, and 5 utilized other CAs [52, 54, 117, 118, 127]. The GW comprehensiveness of evaluation 1 totaled 32 articles for non-comprehensive, 25 for partially comprehensive, and 5 for comprehensive; evaluation 2 yielded Unlikely (26), Possibly (31), and Extremely (5); evaluation 3 gave No (30), Yes (32); evaluation 4 gave No (36), Yes (26). Rest-1 time ranged from immediate to 15 min, with 27 studies not reporting specific times. Rest-2 time ranged from immediate to 15 min, with 19 studies not reporting specific times. Rest-3 time after the CA ranged from immediate to 30 min. Regarding the modality of measurement, 41 studies performed more than two performance tests during Rest-3 time, and 21 performed only one performance test. At least 40 studies reported test results for jump performance [$ES(n) = 198$], 21 reported sprint performance [$ES(n) = 148$], 9 reported upper body performance [$ES(n) = 79$], and 4 reported agility performance [$ES(n) = 13$]. Fifteen studies measured more than two types of performance simultaneously [41, 43, 44, 48, 52, 66, 78, 89, 118, 121, 123, 127, 133, 136, 139].

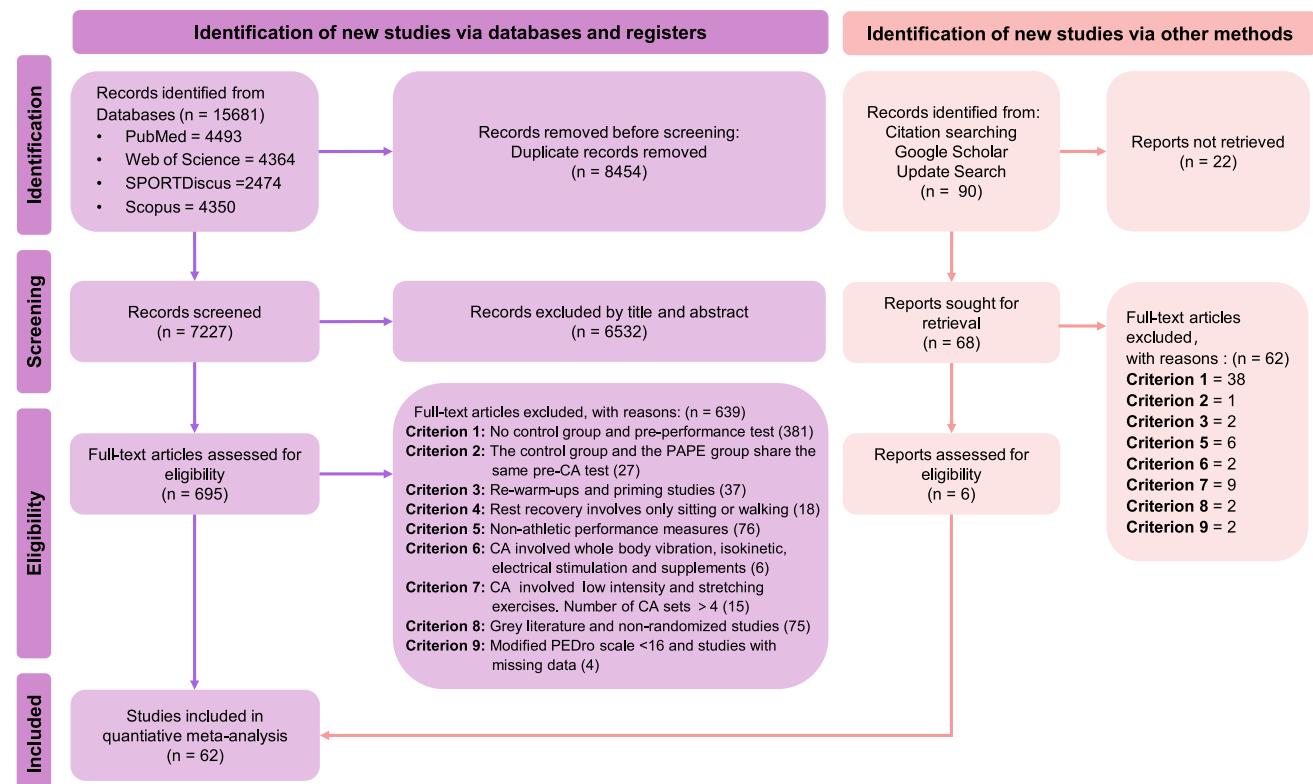


Fig. 2 PRISMA flow diagram detailing the study inclusion process

3.3 Risk of Bias and Quality Assessment

All included studies mentioned randomization in their studies, but only 12 studies [41–43, 47–49, 63, 67, 78, 89, 133, 142] reported the specific method of randomization. Therefore, these were rated as “low risk,” while all others were rated as “unclear risk.” Only two studies [85, 133] set up blinding of testers; no other studies reported information on blinding. Three studies [47, 69, 119] experienced attrition in sample size, so attrition bias was unclear risk, while all others were rated as “low risk.” Nine studies [31, 45, 67, 69, 85, 117, 119, 135, 136] performed more than two familiarization experiments and were therefore rated as “low risk,” while 37 studies performed one and 16 studies performed no familiarization. One study [52] did not conduct a familiarization, but the participants in that study had previously undergone a similar experimental process [118]. Therefore, the study [52] was assessed as “unclear.” A total of 23 studies measured multiple time points with intervals <4 min and were therefore “high risk,” while 20

studies measured time intervals ≥4 min and were therefore “unclear risk.” Fifteen studies took measurements at a single time point only and were therefore “low risk.” The Rest-3 time of one study [52] was selected as the best value of previous studies, most of which were around 7–9 min, and the mean value of 8 min was selected for data analysis in this study. Sixteen studies [41, 44, 47–49, 52, 59, 63, 67, 79, 85, 125, 132, 137] reported more than two indicators of measurement reliability at the same time, 27 studies reported only one, and 19 did not report measurement reliability, and were therefore rated as “high risk.” Nineteen studies performed a priori sample size estimation calculations. However, only six studies [29, 46, 68, 132, 136, 140] performed the estimation correctly. Fourteen studies [44, 48, 49, 52, 53, 66, 67, 79, 117, 118, 128, 137, 141] applied the ES of the *t*-test for estimating the effect size of the *F*-test and were therefore rated as “high risk.” Forty-three studies did not perform a priori sample estimation calculations, of which seven studies [61, 69, 71, 96, 128, 134, 138] had a sample size of <10 individuals and

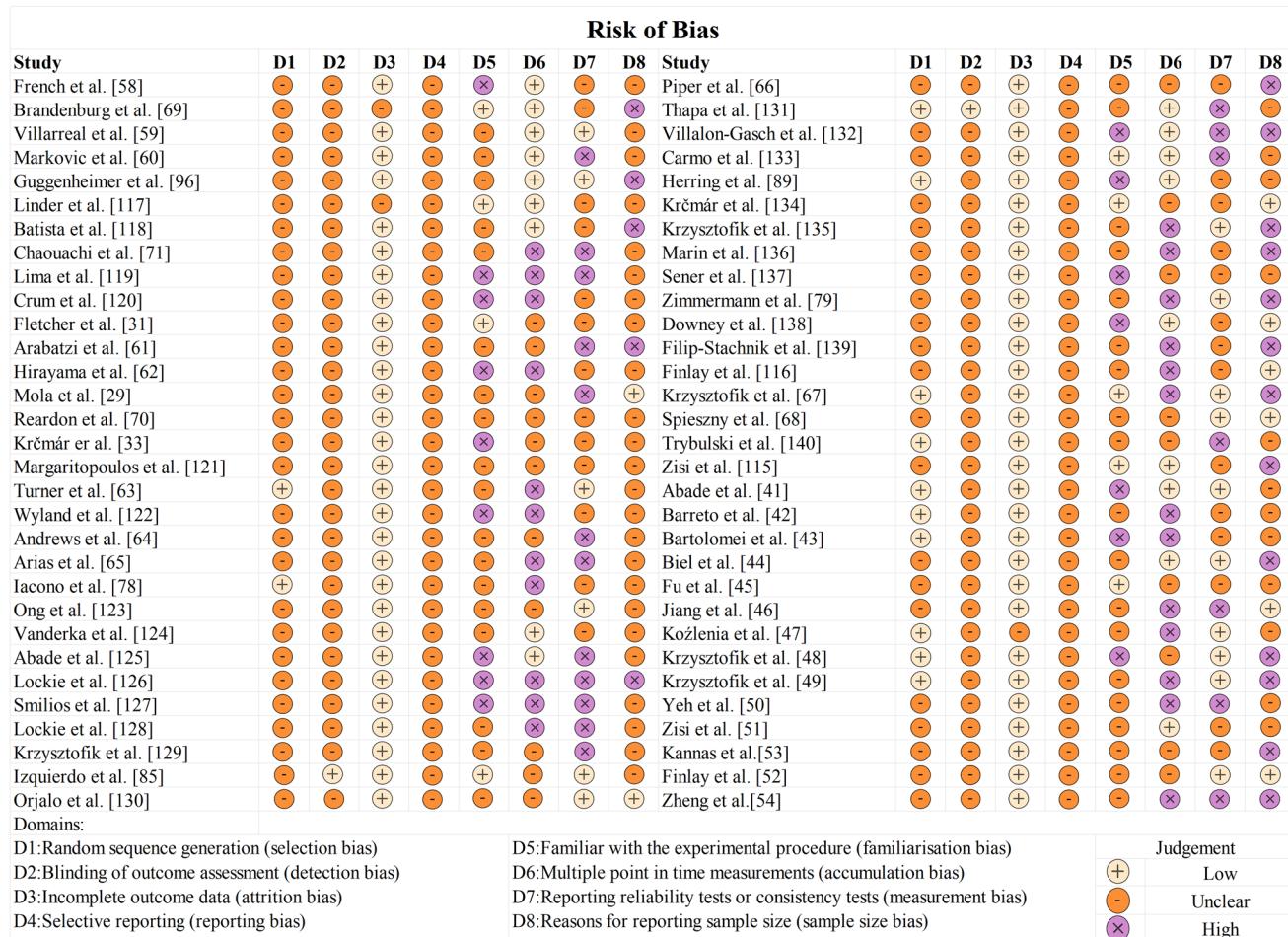


Fig. 3 Risk of bias assessment for all included studies

were consequently rated as “high risk.” The other studies were “unclear risk” (Fig. 3).

The modified PEDro scores of the included studies ranged from 16 to 20, with a mean score of 17.5. The overall risk of bias in the included studies was “high”; however, the methodology implementation and reporting process was relatively complete.

3.4 Risk of Publication Bias and Certainty Assessment

Egger's regression test showed that PAPE versus control group ($p < 0.001$, Fig. 4A), PAPE group pre- versus post-CA ($p < 0.001$, Fig. 4B), and control group pre- versus post-CA ($p = 0.026$, Fig. 4C) performance test study designs were at significant risk of publication bias at level 2 (within-study variance), and only the PAPE versus control group design ($p = 0.040$, Fig. 4D) was at simultaneous risk of publication bias at level 3 (between-study variance). Egger regression lines and the prediction line for sampling variances between PAPE group pre- versus post-CA, and control group

pre- versus post-CA at level 3 were close to overlapping (Fig. 4E, F). Therefore, there was no significant risk of publication bias. Seitz et al. [7] explained the risk of publication bias with a large number of studies reporting byproducts in the same direction (i.e., increase in performance after a CA). However, as can be seen from Fig. 4, the overall ESs in level 3 were more symmetrical and the results were not significantly skewed toward positive ESs. Observation of Fig. 4 reveals a difference in standard errors between positive ES and negative ES, with several studies having very large standard errors. Therefore, the observed risk of publication bias in the present study may be a reduction in precision owing to the small sample size in the original studies. In addition, the risk of publication bias observed at level 3 in the PAPE versus control group design may be caused by the overall standard error becoming larger in the PAPE versus control group comparison.

Evidence of overall certainty for all three comparisons was low, mainly owing to the high risk of bias and the direct presence of inconsistent populations in the studies, CA modalities, and measurement outcomes (Table 3).

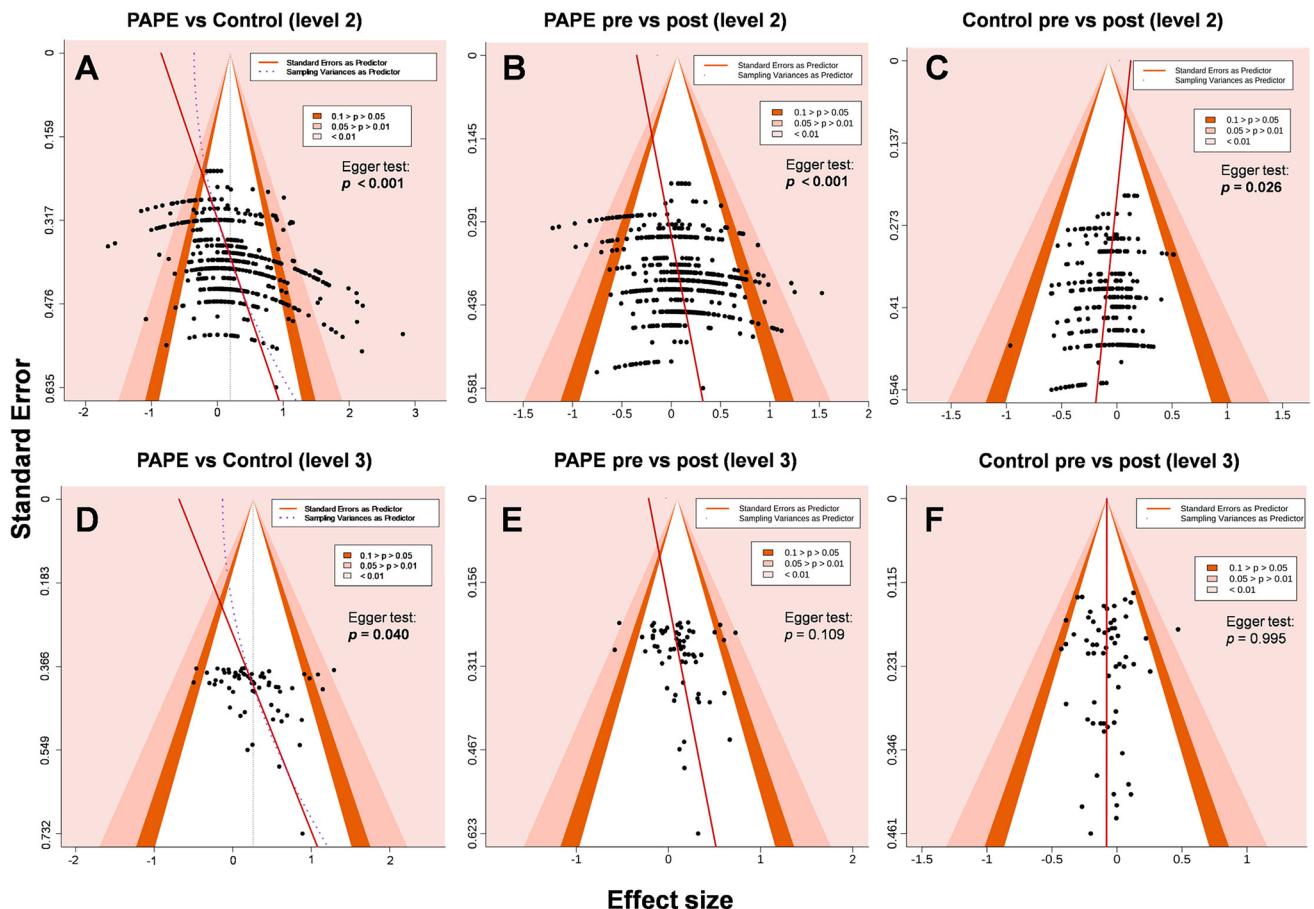


Fig. 4 Risk of publication bias at levels 2 and 3. *A, D* PAPE versus control at level 2 and 3; *B, E* PAPE pre- versus post-CA at level 2 and 3; *C, F* control pre- versus post-CA at level 2 and 3; *PAPE* post-activation performance enhancement, *CA* conditioning activity

Table 3 GRADE assessment for the certainty of evidence

Certainty assessment						No. of participants			Certainty
No. of studies	Risk of bias	Inconsistency	Indirectness	Imprecision	Publication bias	PAPE	Control	Absolute (95% CI)	
PAPE versus control (3–12 min)									
62	Serious	Serious	Serious	Not serious	Not serious	964	955	ES 0.30 (0.20 to 0.40)	⊕⊕○○ Low
PAPE pre versus post (3–12 min)									
62	Serious	Serious	Serious	Not serious	Not serious	964	964	ES 0.12 (0.06 to 0.19)	⊕⊕○○ Low
Control pre versus post (0–30 min)									
62	Serious	Serious	Serious	Not serious	Not serious	955	955	ES -0.08 (-0.13 to -0.03)	⊕⊕○○ Low

PAPE post-activation performance enhancement, ES effect size, CI confidence interval

3.5 Main Effect

Sixty-two studies provided a total of 596 ESs. The number of ESs was reduced to 438 after intercepting ESs with Rest-3

times of 3–12 min. Comparison of traditional meta-analyses revealed that three-level meta-analysis showed better fit [Table S3 (ESM)]. Therefore, a three-level meta-analysis was used for further analysis.

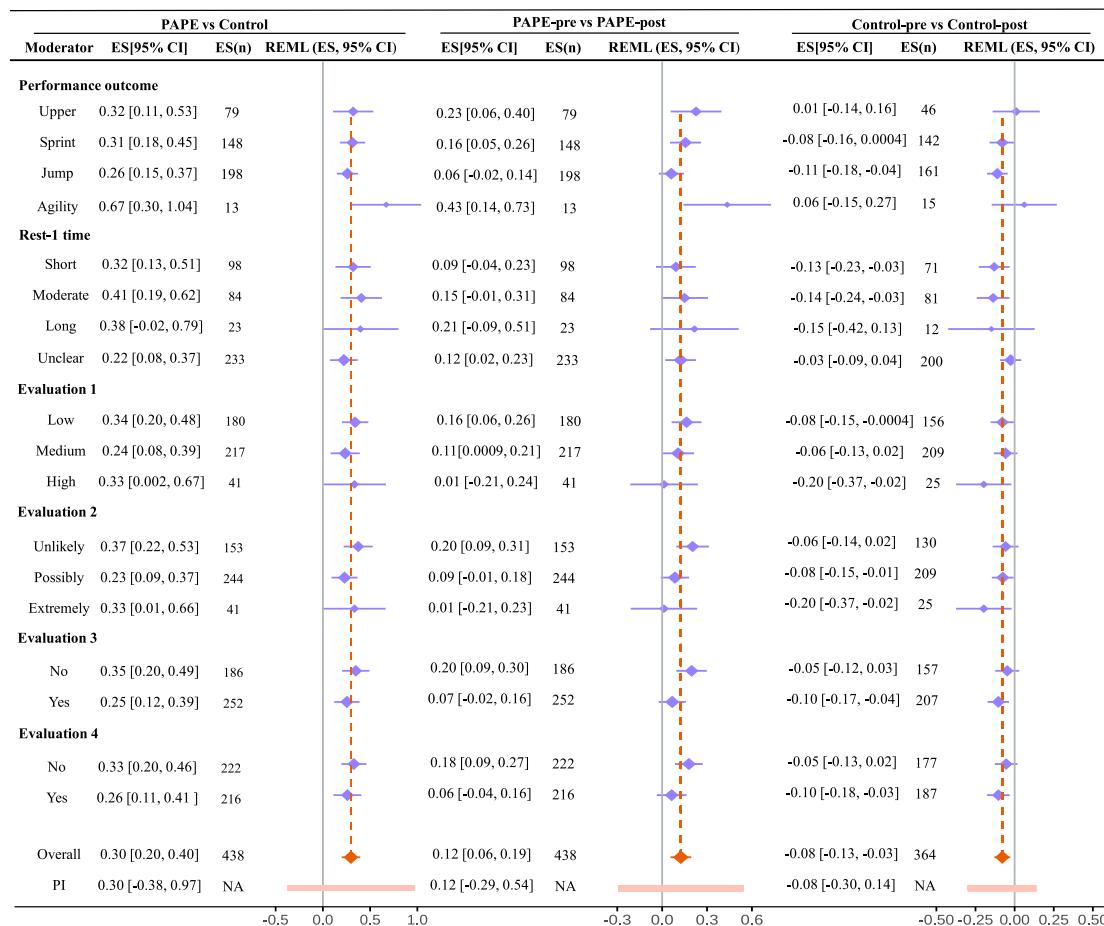


Fig. 5 Results of subgroup analyses of different comparison modalities. ES effect size, REML restricted maximum likelihood, PI prediction interval, ES(n) number of effects size(s), GW general warm-up,

Rest-1 time time from general warm-up to pre-CA test, NA not applicable, Evaluations 1–4 subjective evaluation of the general warm-up, as detailed in Table 2

In studies using the PAPE versus control group design, the PAPE effect was small overall ($ES = 0.30$, 95% CI [0.20 to 0.40], $p < 0.001$, $Q(437) = 779.0$, $p < 0.001$, I^2 -level 2 = 0%, I^2 -level 3 = 43.9%, PI = -0.38 to 0.97, Fig. 5) and for jump (ES = 0.26), sprint (ES = 0.31), and upper-body (ES = 0.32) performances separately, but moderate for agility performance (ES = 0.67). Evaluation 1 of GW showed that the PAPE effect was similar at low (ES = 0.34) and high (ES = 0.33) GW intensities. There were no significant differences between any of the other evaluation results for GW. The PAPE effect was more effective in Rest-1 with moderate recovery times (ES = 0.41) than short (ES = 0.32) and long (ES = 0.38) recovery times (Fig. 5). There were no main, simple, or interaction effects between Rest-1 and GW comprehensiveness on PAPE. There was a significant combined effect of the different evaluation results for GW with short and moderate recovery times for Rest-1 time (see Supplement 11 in the ESM).

Further to the PAPE versus control group design, the results of subgroup analyses of participants' characteristics showed that highly trained athletes (ES = 0.38) responded more to CAs than trained populations (ES = 0.21) and

physically active individuals (ES = 0.22, Fig. 6). Participants with ≥ 2 years' training experience (ES = 0.36) also responded more than those with < 2 years' training experience (ES = 0.16), and females (ES = 0.51) responded more than males (ES = 0.32) and the mixed group (ES = 0.16). However, no statistically significant differences ($p > 0.05$) were found between groups for participant characteristics. Subgroup analyses of CA types showed that plyometric exercise (ES = 0.43) had a greater effect on PAPE amplitude than maximal voluntary isometric contraction (ES = 0.31), traditional resistance exercise (ES = 0.23), and other exercise modalities (ES = 0.24, Fig. 6). A significant difference was found between plyometric and traditional resistance exercise ($p = 0.02$). Additionally, the effect of multiple sets (ES = 0.31) was greater than that of a single set (ES = 0.27), although this difference was not statistically significant ($p = 0.67$).

PAPE group pre- versus post-CA study designs showed a trivial PAPE effect on athletic performance (ES = 0.12, 95% CI [0.06 to 0.19], $p < 0.001$, $Q(437) = 326.9$, $p < 0.001$, I^2 -level 2 = 0%, I^2 -level 3 = 23.2%, PI = -0.29 to 0.54, Fig. 5), including for jump (ES = 0.06) and sprint (ES = 0.16)

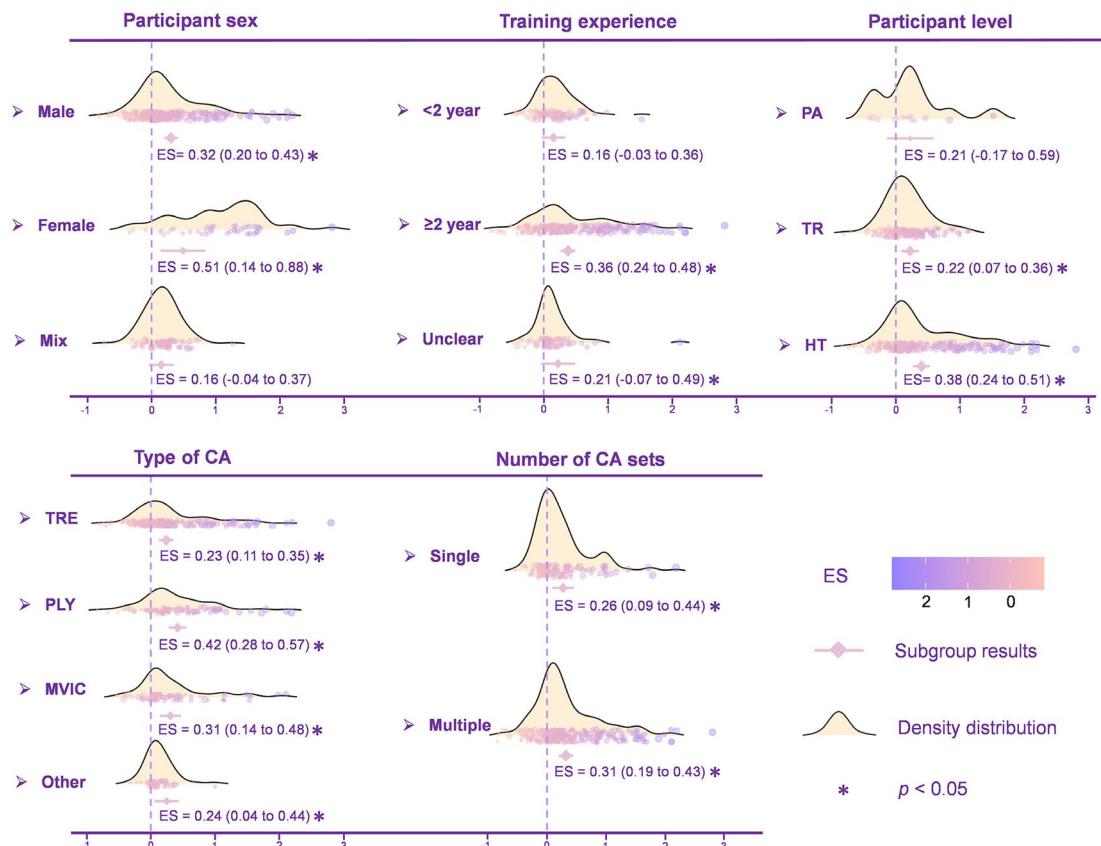


Fig. 6 Subgroup analysis of participant characteristics and CA type. PA physically active, TR trained, HT highly trained, TRE traditional resistance exercise, PLY plyometric, MVIC maximum isometric vol-

untary contraction, Other other CA methods include resisted sprint training, elastic bands training, CA conditioning activity, ES effect size

performances, although the effect was small for upper-body ($ES = 0.23$) and agility ($ES = 0.43$) activities (Fig. 5). There were no significant differences in PAPE effects for different recovery times at Rest-1. All four GW evaluations showed that PAPE was greatest when GW was not comprehensive.

Control group pre- versus post-CA analyses showed that rest had a trivial detrimental effect on athletic performance ($ES = -0.08$, 95% CI [-0.13 to -0.03], $p = 0.002$, $Q(363) = 118.3$, $p = 1.000$, I^2 -level 2 = 0%, I^2 -level 3 = 7.9%, PI = -0.30 to 0.14, Fig. 5), with both short ($ES = -0.13$) and moderate ($ES = -0.15$) Rest-1 times having significant and trivial detrimental effects. The results of the four GW evaluations indicated that a comprehensive GW significantly reduced exercise performance in controls.

Selecting the best-valued observations in the control group and combining them did not reveal a significant cumulative effect [$ES = 0.03$, 95% CI [-0.06 to 0.13], $p = 0.463$, $Q(61) = 12.4$, $p = 1.000$, I^2 -level 2 = 0%, I^2 -level 3 = 0%, PI = -0.06 to 0.13, Fig. S1 (ESM)]. Sensitivity analyses showed that changing the analysis method, excluding outliers, and sequentially removing individual ESs had no significant effect on the results. The results of the three-level meta-analysis had better goodness of fit (for more details, see osf.io/v7sbt).

3.6 Linear and Nonlinear Meta-regression

Control group pre- versus post-CA study design analyses revealed no significant linear relationship between PAPE magnitude and Rest-3 time ($\beta = -0.005$, $p = 0.149$, Fig. 7G).

The nonlinear meta-regression results for the PAPE group pre- versus post-CA designs revealed an overall inverted U-shape relationship between the PAPE effect and Rest-3 time (Fig. 7A). PAPE effects were observed in the range of 2.5–11 min, with an optimal time point at 5.5 min. Further categorization based on performance results revealed enhancement intervals of 4.5–6.3 min for jump (Fig. 7B), 3.6–8.6 min for sprint running (Fig. 7C), and 3.6–11.0 min for upper body performances (Fig. S2A [ESM]).

For the PAPE versus control group design, the results revealed an inverted U-shaped trend between Rest-3 time and PAPE magnitude (Fig. 7D). In this case, PAPE effects were observed in the range of 1.5–20.5 min with an optimal time point at 5.8 min. Further categorization based on performance results revealed enhancement intervals of 1.8–18.6 min for jump (Fig. 7E), 3.0–11.8 min for sprint (Fig. 7F), and 3.0–10.7 min for upper body performances (Fig. S2D [ESM]). Furthermore, we observed that the percentage of 1-RM for traditional resistance exercises (meaningful interval 69–104%, Fig. 8A), the total number of plyometric exercise repetitions (meaningful interval 8–30.4, Fig. 8B), and the total duration of

isometric contractions (meaningful interval 7.5–12 s, Fig. 8C) showed weak inverted-U trends with PAPE amplitude.

Owing to the limited number of studies with agility as an outcome, no clear trends were observed (Fig. S2B, E [ESM]). Further analysis of studies showing a PAPE effect within 1 min indicated that PAPE could be produced immediately post-CA and gradually decreased with recovery time (Fig. 7H).

The results of the nonlinear regression on the moderator variables Rest-1 and Rest-2 time are shown in Fig. S2C, F, G, H (ESM). According to the *loess* model, the greatest PAPE magnitude was observed at 3–5 min for both between-group and within-group comparisons (Fig. 9). It is worth noting that the nonlinear regression model for these results was not robust.

4 Discussion

The main objective of this review was to explore the influence of general warm-up (GW) and experimental design on the magnitude and timing of CA-induced PAPE effects. We also explored the influence of different moderators, including comparison methods, participants' characteristics, CA parameters, outcome measures, GW comprehensiveness, and recovery durations, on PAPE magnitude. The current analyses revealed that (1) PAPE study designs showed a high risk of bias, including a lack of condition randomization and its reporting, participant and tester blinding, procedure familiarization, cumulative effects of repeated tests (e.g., learning or fatigue effects), measurement reliability, and a priori sample size estimation; (2) PAPE within-group comparisons revealed only a small effect of CAs on athletic performance, but control groups tended to decrease in test performance overall, thus enhancing the observed PAPE magnitude and ensuring the PAPE versus control group study design produced greater PAPE magnitudes than non-controlled studies; and (3) participant characteristics (sex, training level, training experience), CA type (e.g., traditional resistance exercise, plyometric exercise), test type (e.g., sprint run, throw, vertical jump, etc.), GW comprehensiveness, and Rest-1 recovery time (i.e., between GW completion and baseline [pre-CA] testing) also influenced PAPE magnitude (as discussed in Sect. 4.2). Overall, an inverted-U pattern of enhancement of PAPE recovery time was observed with maximum PAPE magnitude observed at about 5.5 min post-CA, although PAPE magnitude was trivial ($ES = 0.01$) when a comprehensive GW was performed before baseline testing.

4.1 Risk of Bias in Experimental Design

4.1.1 Randomization and Blinding

Condition (i.e., CA versus control) randomization and blinding of both participants and tester are crucial methods for

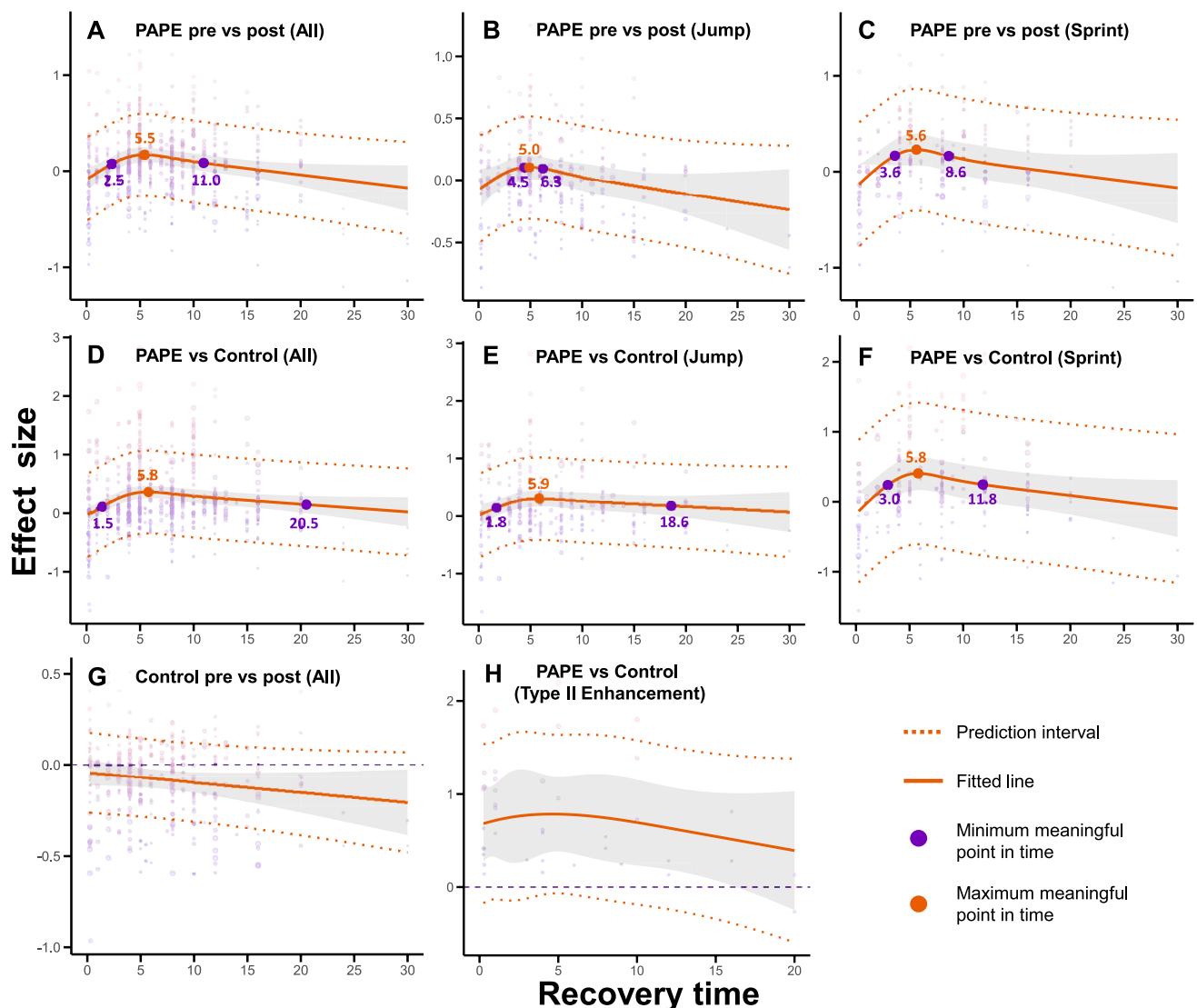


Fig. 7 A–C Results of nonlinear meta-regression of total outcome, jump, and sprint performances to Rest-3 time in PAPE group pre-versus post-conditioning activity. D–F Results of nonlinear meta-regression of total outcome, jump and sprint performances to Rest-3 time in PAPE versus control group. G Results of linear meta-regres-

sion of total outcome to Rest-3 time in control group pre- versus post- conditioning activity. H Nonlinear meta-regression of the PAPE effect for type II enhancement and Rest-3 time; PAPE post-activation performance enhancement, Rest-3 recovery time after conditioning activities

minimizing bias and enhancing both internal and external validity in clinical studies [84, 143, 144]. Although all 62 studies included in this review mentioned randomization, only 12 studies [41–43, 47–49, 63, 67, 78, 89, 133, 142] detailed the specific procedures used for randomization. The lack of detailed reporting on randomization procedures could increase the risk of bias. Additionally, none of the studies implemented allocation concealment or participant blinding. Notably, 56 studies used a randomized crossover design, where each participant completed all conditions of the experiment, complicating the implementation of allocation concealment and participant blinding. In this context, Vasconcelos et al. [36] proposed an alternative approach to

mitigate bias risk by informing participants that the study's aim was to evaluate the reliability of the effects of CAs, such as PAPE interventions. Although this approach does not prevent participants from being aware of the CA, it may reduce systematic biases that arise from condition awareness, as participants are likely to expect both CAs to be equally effective. It may also be of use to ask participants their outcome beliefs before study commencement (and after the CA), to determine whether the study outcome is consistent or not with that belief (i.e., whether there may be confirmation bias), as has been done in studies of the acute effects of muscle stretching on post-warm-up performance [145]. In addition to this, only two studies [85, 133] implemented tester

Fig. 8 A Nonlinear meta-regression results between different percentages of 1-RM and PAPE in traditional resistance training. B Nonlinear meta-regression results between total number of training sessions and PAPE in plyometric exercise. C Results of nonlinear meta-regression between total duration of maximal voluntary isometric contractions (MVIC) and PAPE. PAPE post-activation performance enhancement

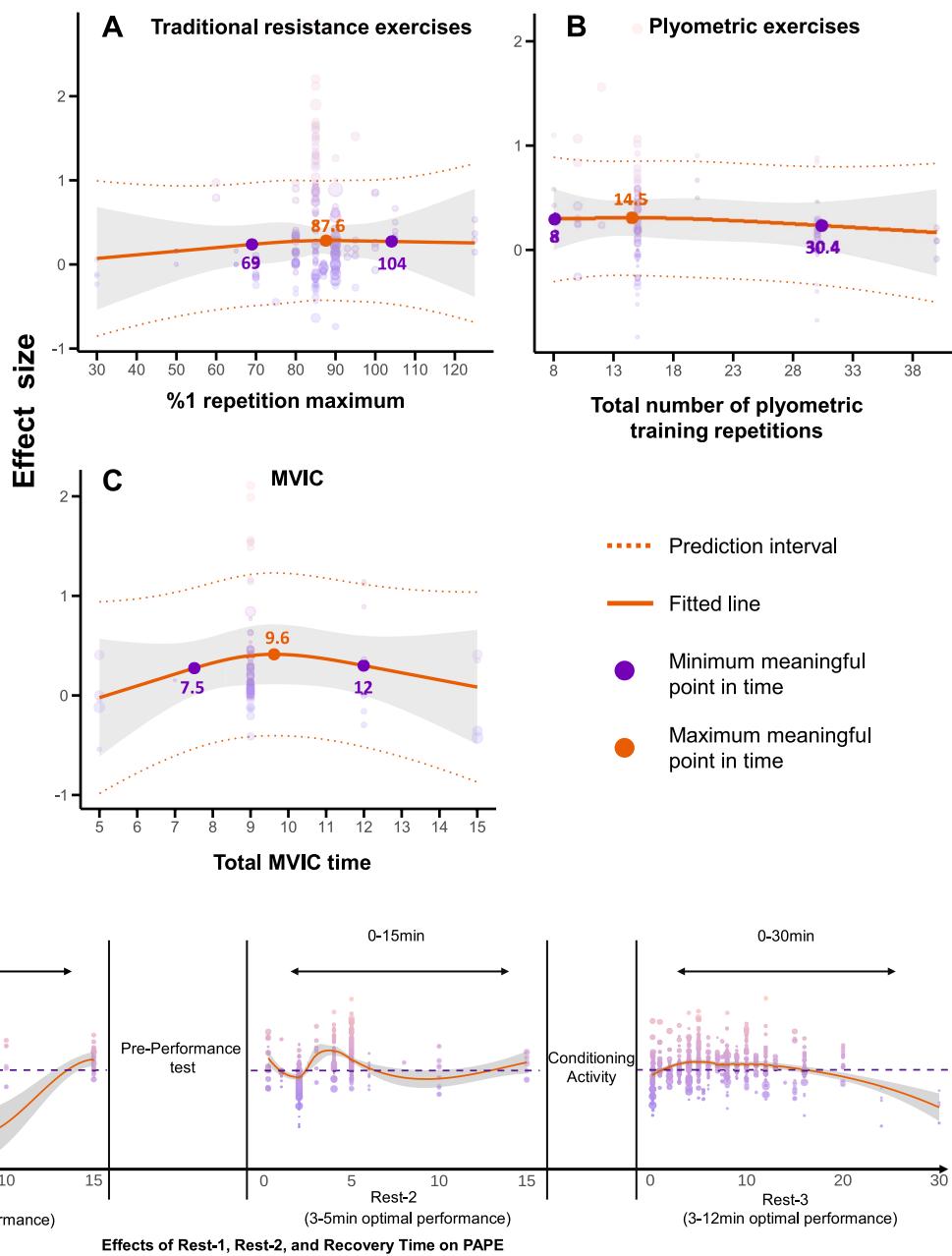


Fig. 9 Effects of Rest-1, Rest-2, and Rest-3 times on PAPE (pre- versus post-CA design). The greatest PAPE effects were obtained when Rest-1 and Rest-2 recovery times were 4 min and 3–5 min. The greatest PAPE effect was also obtained when the performance test was

performed between 3 and 12 min after conditioning activity (Rest-3). Note: The model was fitted using a *loess*, which did not take into account the between-study variance [Fig. S2C, F, G, H (ESM)]

blinding, which is essential as it is both cost-effective and straightforward to execute, yet underutilized. Tester blinding helps prevent researchers from inadvertently influencing participant performance during interventions [84]. It can be speculated that, in real-world scenarios with trained athletes, the influence of these bias sources might be lessened owing to their higher motor skills, adaptability, and ability to control performance, thus increasing the ecological validity of the procedures.

Future studies should prioritize condition randomization and tester blinding and report these procedures comprehensively. Additionally, they should explore the feasibility of participant blinding, which could minimize systematic bias, or at least report participant pre-study beliefs. If these methodological practices are unfeasible in real-world settings, the reasons should be transparently explained.

4.1.2 Experimental Familiarization

Several previous reviews have emphasized the importance of test and CA familiarization to enhance research accuracy [9, 28, 35]. The primary purpose of familiarization, which includes both on-the-day and earlier sessions of familiarization, is to reduce potential learning effects [9, 35], thereby decreasing data variability. Evidence indicates that participants can enhance athletic performance through practice alone, regardless of any PAPE effect, so post-CA performances can feasibly be greater than pre-CA performances simply because of test familiarization. Additionally, however, familiarization with the entire CA-testing process might also affect study outcomes. For instance, Comyns et al. [146] had rugby players perform a 30-m sprint test four times following a squat lift CA and noted a post-CA performance decrement on the first test day that was not observed in the subsequent three sessions (between-session difference, $p=0.036$); so, while no PAPE was ultimately observed, the results of sessions 2–4 were clearly different from those of session 1. Although it cannot be conclusively stated that the participants were influenced by psychological factors such as a stronger belief in CA efficacy, these results suggest that repeated identical experimental procedures may influence PAPE magnitude. These findings are consistent with those of Hopkins et al. [147], who, in their meta-analysis on the reliability of physical performance, reported that performance improved by 1.2% between the first two experimental sessions and only 0.2% in subsequent sessions, suggesting that the performance of only a single familiarization session might be sufficient to minimize possible future learning effects. The reviewed literature shows that only 9 studies conducted more than two familiarization sessions, while 37 included one session and 16 had none. This indicates that only 14.5% of PAPE studies implemented strategies to minimize learning effects, and in 25.8% of studies the PAPE effects may entirely result from these effects.

Alternatively, considering that PAPE may be also attributable to muscle memory mechanisms [13, 14] and that performance enhancement occurs when the potentiation effects are greater than fatigue, thus confirming physiological adaptations to loading [15, 148, 149], we may also suggest that some degree of physiological adaptation may be associated with those improvements after a few sessions. In this regard, further studies may elucidate how much of these improvements may be related to both learning effects and physiological adaptations with appropriate study designs.

Consistent with the recommendations of Hopkins et al. [147] and several other reviews [9, 28, 35], it is advisable for PAPE studies to include at least one familiarization session, though ideally more, to minimize learning effects. In athletes already well acquainted with the procedures, this

source of bias is expected to be negligible, but it should be explicitly reported.

4.1.3 A Priori Sample Size Estimation

Insufficient statistical power can increase both type I and type II error rates, thereby increasing the likelihood of false-negative and false-positive results [150, 151]. Traditionally, researchers have employed a priori sample size estimation to minimize these error probabilities. However, only 18 (29.0%) out of the included studies reported utilizing an a priori sample size estimation procedure, and 13 of these studies incorrectly applied ES values from *t*-tests to estimate sample size for studies using *F*-test (ANOVA) methodologies. Notably, the ES values for *F*-tests typically range from small to large (0.10, 0.25, and 0.40), whereas for the *t*-tests, these boundaries are set at 0.20, 0.50, and 0.80 [86]. Thus, using *t*-test ES values for *F*-tests results in sample size underestimation. For instance, Filip-Stachnik et al. [141] set the significance level at 0.05, statistical power at 80%, and the ES at 0.38 for their test using “ANOVA, repeated measures, within factors,” leading to a required sample size of only nine individuals. However, this estimate was consistent with *t*-test values. When we recalculated the required sample size using appropriate *F*-test ES values based on the authors’ methodology, the correct minimum sample size increased to 33 individuals. Such discrepancies in a priori sample size estimates may contribute to the generally small sample sizes observed in PAPE studies. The median sample size across the 62 studies in this review was 14 individuals, with 8 studies having fewer than 10 participants per condition [61, 69, 96, 120, 128, 130, 134, 138]. This likely indicates that many studies in the current PAPE literature are statistically underpowered, leading to observed increases (PAPE) and decreases (“fatigue”) in performance that may be partly due to lack of statistical efficacy. In populations of elite athletes, sample size estimation becomes practically challenging owing to the limited number of available participants. Moreover, given the small magnitudes of PAPE effects, which often hover around the minimum meaningful threshold and are influenced by numerous factors (e.g., population characteristics, CA characteristics, test type), accurate a priori sample size estimation may not be feasible [26]. Consequently, when precise sample size estimation is not possible, it is advisable for researchers to report results with an emphasis on individual responses, potentially using methods such as spaghetti plots, and incorporate alternative statistical approaches such as Bayesian analysis, CIs, and ESSs to better assess the likelihood of observing a true PAPE effect.

Therefore, future PAPE studies should, when feasible, perform an a priori sample size calculation to enhance the validity of their findings. It is critical to differentiate between

ES values appropriate for *t*-tests and those for *F*-tests. Additionally, focusing on individual responses and employing varied descriptive metrics such as Bayesian analysis, CIs, and ESs can provide a more nuanced understanding and validation of the results obtained.

4.1.4 Repeated (Post-CA) Testing Effect

The performance-enhancing or performance-reducing effects of repeated post-CA testing are recognized as potential factors influencing outcomes in PAPE studies [9, 13, 14, 26, 28, 55], yet no studies have explicitly quantified these effects. In this meta-analysis, we assessed the magnitude of the repeated testing effect by comparing the best performance observed post-CA with the baseline of the control group or condition, where participants engaged only in GW and testing procedures. The most significant cumulative effect size noted was of moderate magnitude ($ES = 0.51$) in one study [124], with another study reporting a 5.4% improvement in jumping performance within the control group [53]. The likely cause of these outcomes could be the brief rest intervals between measurements (<2 min). Despite these instances, the overall results from the control groups did not reveal a significant effect ($ES = 0.03, p = 0.465$), suggesting that repeated testing has, at most, a minor effect on PAPE outcomes. However, when analyzing pooled results from tests at all time points before and after CAs in the control group, a trivial yet statistically significant reduction was observed ($ES = -0.08, p = 0.002$). This indicates that, although a repeated-test effect may exist, it does not significantly alter the reported PAPE magnitude. More likely, other factors such as fatigue, decreasing muscle temperature, or reduced motivation may contribute to a performance decrease. This analysis provides no evidence to support the notion that multiple test iterations either enhance or diminish PAPE effects.

Consequently, future PAPE studies should consider avoiding the administration of several post-CA tests at intervals shorter than 2 min. While no significant cumulative effect was observed when test intervals ranged between 2 and 4 min, it is recommended that recovery time intervals should ideally exceed the phosphocreatine 95% recovery time, which is at least 4 min [152, 153]. This adjustment could help ensure more accurate PAPE assessment and reduce the potential confounding impact of insufficient recovery between tests.

4.1.5 Measurement Reliability

Test reliability pertains to the consistency or reproducibility of performances when a test is repeated [147, 150, 154]. In PAPE studies, which often involve multiple test repetitions within a single session [48, 49, 79, 118] and

across days [58, 59, 63, 124], the validity of observed performance enhancements hinges on the reliability of the test to provide an appropriate signal-to-noise ratio. Factors such as learning effects [155], inaccuracy of individual repeated measurements [154], measuring equipment inaccuracy [147], and daily biological variability [156] can all compromise measurement reliability. Despite the importance of these considerations, only 43 studies (69.3%) in our review reported reliability outcomes. Of these, 16 studies presented two or more measures simultaneously, 27 reported only one measure, and 19 studies failed to provide any information on measurement reliability.

The intraclass correlation coefficient (ICC), which measures relative reliability, was the most commonly reported statistic (used in 41 studies), followed by the coefficient of variation (CV), which assesses absolute reliability (reported in 14 studies). The ICC is particularly useful for assessing the consistency of measurements across multiple assessments or different days [157], while the CV provides insights into the stability of measurements within a single day [147, 154].

Given the critical role of test reliability in interpreting PAPE study outcomes, it is essential for future research to comprehensively report both ICC and CV values. This dual reporting approach helps to ensure that any observed effects are not unduly influenced by measurement variability. Additionally, conducting adequate test familiarization sessions before the actual measurements can further mitigate learning effects and other sources of variability, thus enhancing the overall reliability of the results.

4.1.6 Other Risks of Bias

Controlling the risk of bias is crucial for enhancing the methodological quality and strengthening both the internal and external validity of experimental designs. In the current analysis, the prevalent experimental designs used in PAPE studies were found to carry a high risk of bias. Beyond the risks already discussed, additional factors contributing to this bias include circadian variation [158], tester encouragement or feedback [36], environmental temperature [159, 160], participant effort level or motivation [161], diet and physical activity levels on the day of and before the test [9], menstrual status [162], sample size [163], intertest recovery time and activity [164], and lack of pre-trial study registration to avoid omitting variables during publication [165].

To mitigate these risks, future PAPE studies should improve methodological and procedural specificity. This includes providing detailed descriptions of all potential sources of bias and implementing measures to control them.

4.2 Effect of Experimental Design on PAPE

4.2.1 Effects of GW Comprehensiveness and Rest-1 on PAPE

When GW was categorized using the RAMP method, PAPE versus control group comparisons revealed a similar impact of CAs after both non-comprehensive ($ES = 0.34$) and partially comprehensive ($ES = 0.33$) GWs, suggesting that the type of GW did not significantly influence PAPE magnitude. However, for pre- versus post-CA study designs, significant effects were only observed after non-comprehensive GWs ($ES = 0.16, p = 0.001$), suggesting that PAPE was not evoked after comprehensive GWs. More notably, control group performance decrements in pre- versus post-CA study designs were greater after a comprehensive GW ($ES = -0.20$) than partially ($ES = -0.06$) and non-comprehensive ($ES = -0.08$) GWs, indicating a loss in control group (or condition) performance after comprehensive GWs that will affect the likelihood of finding positive PAPE effects. Moreover, subgroup analyses of GW categorized by the inclusion of potentiation or test-specific exercises generally paralleled those sorted by RAMP. Consequently, the performance of a comprehensive warm-up reduces the likelihood of PAPE being evoked but increases the chance of a reduction in control group performance over time, increasing the possibility of observing a PAPE effect. We recommend that GW comprehensiveness, along with the inclusion of potentiation and test-specific exercises, should be collectively considered to objectively assess the efficacy of any CA.

The above results largely support the conjecture of Blazevich and Babault [9] that a comprehensive GW performed prior to a CA may hinder the elicitation of a clear PAPE effect. These findings also provide indirect evidence of potential shared mechanisms between PAPE and GWs. However, the five studies in which PAPE was examined after comprehensive warm-up [41, 89, 96, 127, 134] did not provide detailed GW quantifications, leaving it ambiguous as to whether comprehensive GWs truly affect athletic performance. Only two studies [31, 62] specifically quantified the impact of the GW on performance by conducting pre-GW testing. Fletcher et al. [31] observed that a partially comprehensive GW enhanced jump performance by 7.0%, and further improvements were seen following a back squat CA, which increased jump performance a further 5.2%. Conversely, Hirayama et al. [62] reported that a non-comprehensive GW reduced jump performance by 2.4%, although performance was subsequently enhanced by progressive-intensity back squats by 11%. While the overall performance enhancement was similar in both studies (12.5 versus 11%), a greater PAPE effect of ~11% was noted after the less comprehensive GW. Importantly, a recent study found that PAPE protocols do not further improve jumping

performance compared with a comprehensive and specific GW [166]. Such observations alongside the current meta-analysis results suggest that the extent of GW comprehensiveness may directly impact PAPE magnitude.

Regarding Rest-1 recovery times, PAPE versus control group comparisons revealed that PAPE was similar with moderate ($ES = 0.41$), short ($ES = 0.32$), and long ($ES = 0.38$) recovery times. However, while no significant PAPE differences were observed in pre- versus post-CA study designs, control group pre- versus post-CA analysis revealed a decrement in performance after both short ($ES = -0.13$) and moderate ($ES = -0.14$) Rest-1 times. This phenomenon could be attributed to two factors. First, previous research has shown that a GW at submaximal intensity leads to an immediate improvement in athletic performance, followed by a gradual decline [1, 167]. Such a pattern, occurring within shorter Rest-1 periods, could potentially increase the baseline score significantly, thereby diminishing the calculated PAPE magnitude. Second, Andrade et al. [168] noted a significant decrease in jump performance during the second test ($p = 0.007$) after a 15-min rest following the initial squat jump test. This indicates that prolonged rest could negatively affect performance. Essentially, the elevated baseline test scores coupled with prolonged resting periods contributed to a decline in control group performance. Consequently, while PAPE group performances were unaffected by Rest-1 time, significant PAPE was detected when compared with the decreasing control group performances. Nevertheless, owing to the limited GW descriptions in most studies, it remains unclear which factors specifically influenced the subgroup analysis results. One possibility is that GW comprehensiveness might show a complex interaction with Rest-1 time; however the current results revealed no significant main, interaction, or simple effects related to GW comprehensiveness with Rest-1 times. The one interaction effect observed may simply have resulted from the comparison of intercepts with negative effect sizes, suggesting it might not represent a genuine interaction effect (see Supplement 11 in the ESM).

In addition to the above, the comprehensive GW with short Rest-1 time and non-comprehensive GW with moderate Rest-1 time had similar effects (see Supplement 11 in the ESM). In PAPE versus control group comparisons, studies using a non-comprehensive GW with moderate Rest-1 period had similar effects ($ES = 0.54$) to those in studies with a comprehensive GW with short Rest-1 ($ES = 0.54$). Additionally, in pre- versus post-control comparisons, both GW without potentiation exercises and moderate Rest-1 time ($ES = -0.17$) and GW with potentiation exercises but short Rest-1 time ($ES = -0.18$) had equal PAPE effects, suggesting that performances after a comprehensive GW may follow an inverted U-shaped potentiation pattern characterized by an initial fatigue (or interference) phase followed by

potentiation, and then a later decline due to cool down or motivational decline effects. Because comprehensive GWs include a full “RAMP” sequence of exercises, the potentiation effects might mimic those observed following CA alone [9]. Thus, short Rest-1 time after comprehensive GW might result in lower baseline test values, so pre- to post-CA test comparisons may reveal significant performance enhancements even when the CA itself did not induce a clear PAPE effect. Nonetheless, given the limited number of studies that precisely quantified GW and detailed Rest-1 times, our interpretation of these analytical results remains speculative.

In conclusion, subgroup analysis suggests that PAPE is influenced by GW regardless of its comprehensiveness and duration of Rest-1 time. Thus, both the nature of GW and the timing of subsequent activity play important roles in determining the efficacy of PAPE strategies, whereby comprehensive GWs and (generally) shorter Rest-1 times are associated with a lack of PAPE effect.

4.2.2 Effect of Outcome Measurement and Rest-3 Time on PAPE

PAPE exhibited a more pronounced effect on agility performance ($ES = 0.67$) than jump ($ES = 0.26$), upper body ($ES = 0.32$), and sprint ($ES = 0.31$) performances in the pre- versus post-CA comparisons, with similar trends but slightly smaller effects observed in the PAPE versus control group comparisons. The reduced ES in control group comparisons can be largely attributed to the reduction in performance over time in the control group ($ES = -0.08$, $p = 0.002$), which amplified the apparent PAPE effect. Notably, a trivial and non-significant PAPE was observed in jump performance pre- versus post-CA comparisons ($ES = 0.06$, $p = 0.150$). Consistent with this observation, several existing meta-analyses focusing on jump performance have reported similar findings, suggesting that PAPE may not consistently enhance jump performance [38, 39, 169]. However, the meta-analysis by Seitz and Haff [7] reported a small and significant effect ($ES = 0.30$). This discrepancy may possibly be explained by selectively including the best performance values at each time point when compiling data (although this would need to be confirmed). When only peak values are included, as in Mola et al. [29] for jumping performance at 16 min or Zimmermann et al. [79] for sprinting performance at 2 min, larger and significant effects are often observed. However, these studies typically show significant performance enhancements only at specific time points, with other time points demonstrating no effect or even a decrease in performance. Using only optimal values can thus introduce bias into meta-analysis [40]. In contrast, Singh et al. [37] incorporated average results from intervals between 3 and 10 min, while we have mitigated this risk by including three-level meta-analyses from 3 to 12 min, yielding more

balanced and realistic outcomes. Furthermore, the interaction between fatigue (or interference) and potentiation processes suggests that individual variability could significantly influence outcomes, thus affecting the generalizability of results. Additionally, when analyzing potentiation effects in discrete (e.g., jump) versus cyclic (e.g., sprinting) tasks, it is important to consider that cyclic movements might more reliably reveal potentiation effects owing to a better signal-to-noise ratio associated with repetition [26].

The present analysis showed that there was an overall inverted U-shaped performance enhancement profile of PAPE magnitude with Rest-3 time, which is consistent with the results of many meta-analyses [7, 20, 27, 38, 39, 169–171]. Furthermore, the results of pre- versus post-CA comparisons revealed similar outcomes (Fig. 7A, D). This profile suggests that immediate performance reduction following a CA is predominant. As fatigue and interference effects dissipate more rapidly than the enhancement decreases, a window for optimal PAPE emerges, followed by a gradual return to baseline performance as recovery time extends [7, 13–15, 148]. In the present study, the baseline value was set to an ES of 0, and it was noted that measurements with recovery times exceeding 20.5 min generally fell below this baseline, suggesting that GW may enhance initial performance levels. Importantly, in the PAPE pre-versus post-CA design, recovery times beyond 11 min were progressively lower than the baseline value. In addition, we found that performances in the control group showed a tendency to decrease with Rest-3 ($\beta = -0.005$, $p = 0.149$); theoretically, performance levels in the control group should always vary around the baseline rather than change linearly [79, 85, 118, 141]. The results of subgroup analyses on the comprehensiveness of GW and the Rest-1 recovery times reinforce the notion that GW significantly impacts PAPE, by either increasing or decreasing baseline performances.

In this study, we also extracted the PAPE effects within very short post-CA times of 0–1 min, employing nonlinear fitting techniques as per the theoretical model proposed by Tillin and Bishop [15]. The findings demonstrated an immediate PAPE effect following CA (Fig. 7H). Further analysis across different performance measures revealed an inverted U-shaped enhancement profile for jump, sprint, and upper-body performances [Fig. 7 and S2 (ESM)] but not agility performances. It is important to note that the number of studies with agility as an outcome was small, resulting in wide confidence intervals and prediction intervals [Fig. S2B, E (ESM)]. This suggests a need for further research involving larger datasets to adequately explore the effects of PAPE on upper-body strength and agility performances.

We also found in all nonlinear regressions that CA increased the time range over which PAPE was observed compared with the control groups. For example, the enhancement time in jumping performance changed from

4.5–6.3 min to 1.8–18.6 min, and in sprint running performance it changed from 3.6–8.6 min to 3.0–11.8 min. This further demonstrates that PAPE magnitude was amplified when comparing the intervention group with the control group, therefore suggesting that the CA not only enhanced athletic performance but also prolonged PAPE duration. Another finding was that the optimal time point for PAPE was always about 5.5 min when a sufficient number of studies were available. According to the model of Tillin and Bishop [15], this time point marked when the phosphagen supply system was almost completely restored [152, 153] and fatigue gradually subsides [13, 14]. Thus, owing to various underlying mechanisms such as maintained muscle temperature [9, 19, 172], blood and water flow [9, 19], and nervous system activation [2, 10, 26, 148, 149], athletic performance shows optimal enhancement at about 5.5 min. However, an athlete's response to PAPE was individualized, and changes in CA parameters (e.g., type, load, and interset intervals) and performance testing modalities could have resulted in the optimal time points shifting forward or backward, or showing no response [8]. For example, the optimal time points for PAPE amplitude, as measured by upper-body performance in this study, were 6.7 and 7.4 min. From a practical point of view, we first selected a recovery time of 5.5 min after determining the CA parameters and the performance testing modality. Then, by observing whether PAPE was generated and adjusting the CA parameters, we aimed to achieve the optimal PAPE magnitude. In other words, 5.5 min could have been the recovery time when CA was used for the first time in practice.

On the basis of the discussion of individual responses to PAPE, we can also identify the recovery time of individual responses to PAPE during familiarization sessions. For example, Finlay et al. [52] employed an individualized approach for recovery time after CA, based on their previous studies [118]. If an athlete achieved the best PAPE magnitude 7 min after the CA in a prior experiment, a recovery time of 7 min was used in the subsequent experiment. Including such a protocol in familiarization sessions can help determine the athlete's optimal PAPE response time, which can then be utilized in practice to optimize performance. However, this approach is not without limitations. Two key assumptions have not yet been confirmed: whether athletes will consistently respond to PAPE at a fixed time point (or time interval) with the same CA load parameters, and whether the magnitude of the response will remain consistent. To date, there appears to be a lack of research exploring the consistency of individual responses to PAPE [173].

In conclusion, the findings of this study lend further support to the theoretical model proposed by Tillin and Bishop [15]. Two modes of enhancement were identified for the PAPE effect: an inverted U-shape (e.g., decrement → performance enhancement → return to baseline) and a linear

trend (e.g., performance enhancement → return to baseline). Additionally, the control group comparison underscored an increased PAPE magnitude, likely influenced by whether the GW increased or decreased baseline test performances. We also found that the optimal recovery time point for PAPE was about 5.5 min.

4.2.3 Effect of Participation Characteristics and CA Parameters on PAPE

Consistent with numerous previous findings [7, 8, 20, 27, 28, 120, 174], subgroup analyses of participant characteristics in the present study indicated that participants with high training experience and training level (≥ 2 years) were likely to show greater PAPE magnitudes [175]. It has been speculated that participants with high levels of training experience typically exhibit greater fatigue resistance [7, 174], which may have conferred an advantage in balancing enhancement and fatigue, leading to a greater magnitude of PAPE at an earlier recovery time [7]. Nonetheless, it is not yet definitively determined why individuals with higher training experience and level show a greater PAPE response.

Additionally, we found that female participants had a greater PAPE response than male participants. However, this should be interpreted with caution as only five all-female studies were included, which may indicate a risk of publication bias (i.e., only studies with positive results were published). In fact, no statistically significant difference was observed between the female and male groups, which is consistent with findings of previous research [174, 176]. Considering the relatively small proportion of female participants in PAPE studies (17.5% in the present analyses), future research should further explore the PAPE magnitude in female participants.

Subgroup analysis of different CA types showed that plyometric exercise had a greater effect on PAPE than traditional resistance exercise, maximal isometric contractions, and others. This was similar to the conclusions obtained by Seitz et al. [7], except that we found isometric contractions to have a significant effect on PAPE. Isometric contractions typically show a lower metabolic cost compared with dynamic contractions, meaning that isometric contractions produce less metabolic stress in the balance between enhancement and fatigue, perhaps resulting in less fatigue [48, 177]. Therefore, there is still value in exploring the effect of isometric contraction on PAPE, differentiating also between maximal and submaximal isometric contractions when looking for a greater enhancement–fatigue balance.

Interestingly, we also found that the PAPE effect of plyometric exercise was significantly larger than that of traditional resistance exercise. Plyometric exercises may preferentially recruit type II muscle fibers and therefore might have produced a better enhancement–fatigue balance when

compared with resistance exercises [7]. As a result, the overall magnitude of effect may be greater. This advantage, along with the ease of implementing these exercises in any sport setting, provide further support for their selection as CAs [178, 179]. It is worth noting that, although the majority of resistance exercises consisted of back squats, some exercises might have also served as effective CAs, including power cleans [96], deadlifts [41, 65], variable resistance exercises [124, 136, 138], eccentric overload methods (e.g., flywheels) [45, 85], and supramaximal eccentric exercise (eccentric loading of > 100% of concentric 1-RM) [125]. Additionally, other CA modalities had the potential to induce PAPE effects, including resisted sprint exercises [51], traditional back squats combined with blood flow restriction [54], and elastic band resistance punching [52]. These CA modalities might have demonstrated some advantages in specific performance tests and settings. However, the present analyses did not further explore the specific effects of these strategies because only a limited number of studies using a control group existed for these different approaches (one to three studies per approach). Therefore, future research is needed to explore each method in more detail, particularly including the use of a non-exercise control group.

Finally, we performed nonlinear regressions on the main plyometric exercise, traditional resistance exercise, and isometric contraction loading parameters. The predicted results indicated that traditional resistance exercise induced the greatest PAPE at 87.6% 1-RM. It is important to note that this result was influenced by the fact that the largest number of studies (44.4%) used 85 and 90% 1-RM. We also found that the optimal total number of plyometric exercise repetitions was 14.5 and the optimal total isometric contraction (maximum or sub-maximum) duration was 9.6 s. These findings largely result from the original studies often using plyometric exercises in three sets of five repetitions each (47.4%) and isometric contractions in three sets of 3 s each (58.3%). Therefore, on the basis of the study data and prediction results, we may suggest using 85–90% 1-RM as the optimal resistance exercise load, three sets of five repetitions each for plyometric exercise, and three sets of 3 s for isometric contractions. However, from a practical perspective, plyometric exercise appears to be the most effective and convenient CA method. In addition, these results do not preclude the need for loading individualization in warm-up protocols when searching for optimal PAPE outcomes.

4.3 Rethinking the PAPE Effect: What Really is PAPE?

Currently, CAs are utilized in various sport training scenarios, including warm-ups, re-warm-ups, complex training, priming, testing, and monitoring to evoke a PAPE effect [1, 3, 5, 6, 19, 35, 149, 180–184] with the aim of effecting

acute and, subsequently, long-term performance enhancements [9, 26, 28, 185]. However, on the basis of the current data, PAPE effects appear to be similar in magnitude to GW, likely owing to shared mechanisms such as increased muscle temperature. The GW comprehensiveness therefore impacts PAPE magnitude, making it challenging to enhance the effect of a comprehensive GW by using additional CAs. More importantly, several studies have not found specific CAs to be more effective than GW in enhancing performance [166, 186, 187]. Therefore, if PAPE is insufficient to further enhance athletic performance following a comprehensive GW, including potentiation exercises within a GW may not be justifiable.

Addressing this issue requires the refinement of experimental designs to better distinguish between the effects of CAs versus GW. Current data suggest that, to achieve optimal PAPE, a non-comprehensive GW should be followed by recovery periods of 3–5 min in Rest-1 and Rest-2, and then 3–12 min in Rest-3 (post-CA) (Fig. 9). However, a non-comprehensive GW does not appear to enhance performance effectively [9, 62], and the recovery periods at Rest-1 and Rest-2 can further reduce the effects of GW and pre-CA test performance. Essentially, therefore, observed performance gains are largely attributable to the CA itself. This can be contrasted with findings that a moderate- to high-intensity GW can improve performance immediately and to at least 10 min later [1, 5, 6, 167, 184], indicating that the effects of CAs could also be achieved by a GW of moderate to high intensity, which might then also more perfectly mimic the task with respect to movement pattern (Fig. 7C, D). However, the PAPE effect typically exhibits an inverted U-shaped enhancement pattern. From a practical standpoint, coaches and athletes are likely to prefer a GW of moderate to high intensity over CAs, especially considering that many high-intensity CAs (e.g., squats, power cleans) require a barbell, plates, or sleds, which significantly limits the implementation of CA strategies in sporting and other exercise environments.

Our results unequivocally demonstrate that CAs significantly enhance athletic performance. Specifically, the PAPE effect refers to performance improvements following a maximal- or near-maximal-intensity CA, including plyometric, ballistic, barbell lifting, and other neuromuscular exercises. These high-intensity CAs allow substantial work to be done in a short time to evoke neural and physiological changes (including temperature-related changes) more rapidly than the traditional aerobic exercise plus stretching that is often included in GWs [8–10, 37]. This contributes to the observed inverted U-shaped pattern of performance enhancement associated with PAPE. From this perspective, PAPE serves as a crucial test for the efficacy of any GW, since the addition of a CA to a non-comprehensive GW significantly enhances athletic performance, whereas

its addition to a comprehensive GW does not. Another critical role of CAs is in optimizing the efficiency of warm-ups. An appropriate CA can accelerate performance enhancement [188, 189]. This was exemplified during re-warm-ups in team sports, where a brief, 2-min explosive task could restore athletic performance [6, 184]. In contrast, GWs without potentiation exercises show negligible improvement in athletic performance over the course of a similar 2-min period. Furthermore, compared with a control group, the PAPE group sustained the PAPE effect for up to ~16 min (Fig. 7A).

In conclusion, the PAPE effect could potentially play a role in enhancing sports performance through: (1) testing the adequacy of a GW, (2) enhancing the efficiency of a GW (i.e., greater performance improvement within the available warm-up time), and (3) prolonging the performance enhancement duration. The question of whether the PAPE effect can further enhance athletic performance on the basis of a comprehensive GW remains unresolved and warrants further investigation in future studies.

4.4 Limitations

To the best of our knowledge, this is the first study to utilize a three-level meta-analysis methodology with nonlinear meta-regressions to examine the effects of PAPE. It is important to note that subgroup categorization of moderators of continuous variables, based on meta-analysis results, may be susceptible to selective reporting biases. In this study, both linear and nonlinear meta-regressions were utilized for all moderators with continuous variables to minimize the impact of subjective result interpretation. However, several limitations of this review must be acknowledged. The ratings

of GW comprehensiveness were subjectively determined, and GWs in real-world settings may vary owing to individualization. Notably, there is insufficient direct evidence of the effect of GW on athletic performance. A comprehensive warm-up was not necessarily found to be more effective for athletic performance than a non-comprehensive or partially comprehensive GW when the rest time after GW was not considered [1, 5]. Consequently, the findings from subgroup analyses in this study should be interpreted with caution as they may highlight issues inherent to the current PAPE experimental design (see Sect. 4.5). Despite establishing strict exclusion criteria to enhance the quality and consistency of the studies included, our approach may not have fully captured the comprehensive effects observed across all PAPE studies. A significant number of studies lacked a control group or condition or did not include pre-CA tests, which are essential for adequately assessing PAPE magnitude. Therefore, future more extensive meta-analyses and higher-quality PAPE studies will be required to better determine the overall impact of PAPE.

4.5 Recommendations for Future PAPE Studies

The primary challenge in PAPE research is distinguishing the effect of GWs on PAPE (Fig. 10). GWs, along with variation of Rest-1 recovery durations, may either increase or decrease PAPE effects by either altering the time course of control group (or condition) performances or directly affecting CA efficacy. In response to this challenge, we propose two potential solutions (Fig. 11).

The first proposed solution involves the inclusion of additional testing before the GW, following the PAPE framework outlined in Sect. 1. This testing would help determine

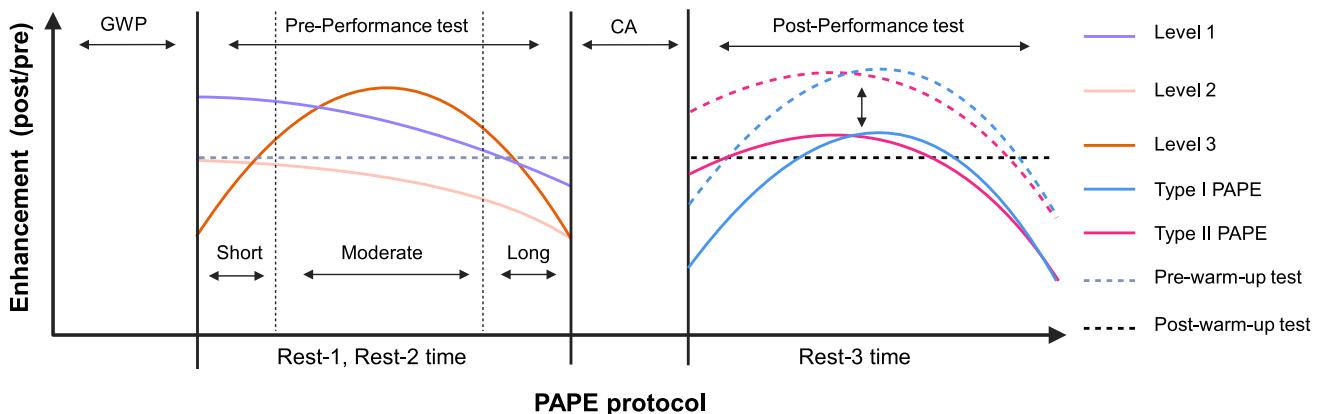


Fig. 10 Theoretical modeling of general warm-up (GW) activities, time from warm-up to CA, and performance test results (pre- versus post-CA). GW may either increase (i.e., PAPE) or decrease (i.e., fatigue) with respect to baseline test performances, directly resulting in higher or lower post-CA outcomes. GW general warm-up, *Level 1* performance improves directly, then gradually declines, *Level 2* per-

formance declines over time, *Level 3* performance showed an inverted U-shaped pattern of enhancement, *Type I PAPE* inverted U-shaped potentiation pattern with fatigue followed by enhancement, *Type II PAPE* inverted U-shaped potentiation pattern for direct enhancement, PAPE post-activation performance enhancement

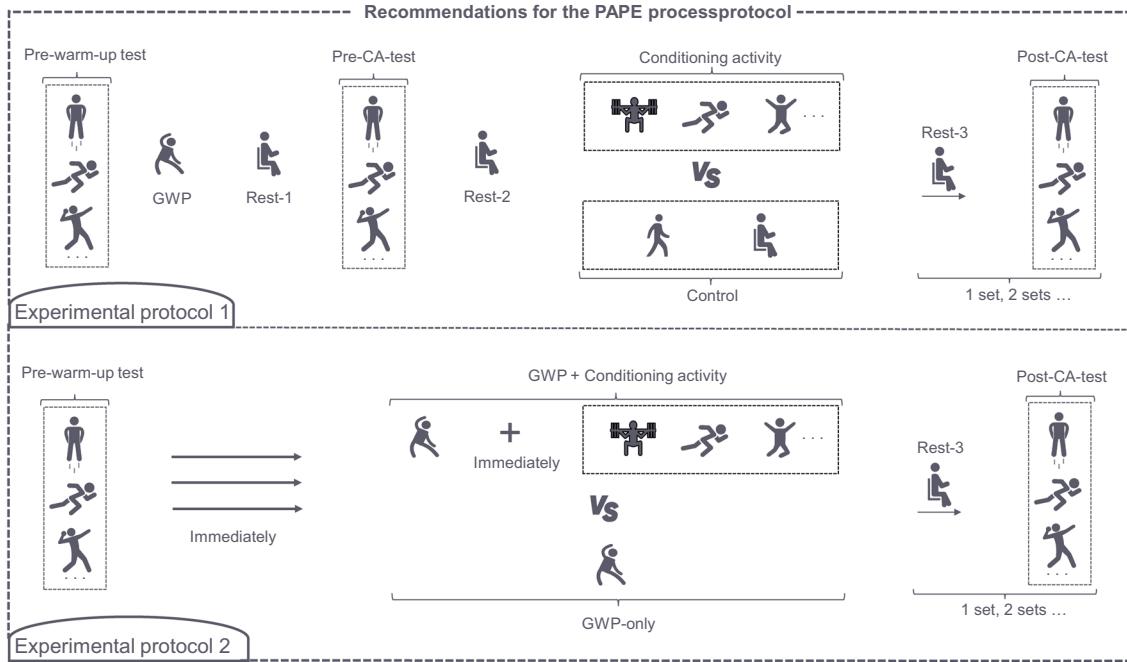


Fig. 11 Experimental protocol 1: add a pre-performance test to the existing process (Fig. 1) to determine the effect of a general warm-up (GW). CA conditioning activity. Experimental protocol 2: elimi-

nate any activity between GW and CA/control condition, and include a pre-GA baseline test. Determine PAPE effect by GW+CA versus GW

whether the GW itself improves performance and then to what extent the CA further enhances it. It is important to note that such a study design closely aligns with studies measuring the effects of re-warm-up and maintaining warm-up efficacy in PAPE settings. This alignment is due to the typical time interval between the GW and the CA, which is a minimum of 3 min in the included studies. Consequently, the second experimental PAPE design shown in Fig. 11 may be more advisable. In this design, any activity between GW and CA is eliminated, and the effect of PAPE is assessed by comparing GW + CA with GW alone. This experimental approach is likely more practical to implement.

When standardizing the GW content, inclusion of a CA can help assess the adequacy of a GW and facilitate the identification of the optimal warm-up conditions through continuous adjustments (i.e., when the CA has no further effect above GW, the GW may be approximately optimum). It is crucial to recognize that both proposed study designs assume that multiple performance tests do not adversely influence test performance and thus PAPE amplitude. Furthermore, if there is a potential risk of injury during maximum pre-CA testing, a series of attempts with progressing intensity (e.g., 20, 40, 60, 80, and 100% effort) might be used.

In addition to refining experimental designs, we recommend that the reporting of PAPE studies should follow the reporting process of randomized controlled trials as closely as possible [190], including pre-registration of the

experiment, calculation of the a priori sample size (distinguishing between effect sizes for *F*-tests and *t*-tests), and randomization (use of randomization techniques and reporting of specific randomization measures). Blinding of testers should be implemented as effectively as possible. Given the challenges of blinding participants, systematic bias may be mitigated by using techniques that obscure the true purpose of the study [36].

In addition to the general statement above, we recommend the following guidelines for future PAPE studies to enhance both reliability and validity:

1. Familiarization sessions: conduct at least one familiarization session, preferably two or more, to minimize learning effects. Alternatively, use common tests that are familiar to participants.
2. Test intervals: while multiple measurements did not appear to significantly impact PAPE magnitudes, test intervals longer than 2 min are recommended, specifically 4 min or more, owing to a moderate effect size ($ES = 0.51$) being observed in the control group for intervals ≤ 2 min.
3. Reliability assessment: both ICC and CV should be reported to provide a comprehensive assessment of measurement reliability.
4. Control of testing environment: maintain strict control over the testing environment, including the time of day,

the interval between tests, participant diet, and physical activity in the days preceding the test. When determining the effect of CAs, oral encouragement during the experimental process should be avoided [36]. Instead, oral encouragement should be used whenever possible in practice.

- Individual data reporting: where possible, report measurements for each participant individually in addition to the overall mean, to provide more detailed insights.

Finally, when confronted with a trained population conducting PAPE experiments, it is advisable to select participants with a high level of training and at least 2 years of training experience, as they are more likely to respond to PAPE. For traditional resistance exercise, we recommend that researchers choose a maximum intensity of 69% 1-RM or higher; for isometric contractions, we recommend a total duration between 7.5 and 12 s; and for plyometric exercise, a total number of repetitions between 8 and 30 should be selected. The recovery time after CA ranges from immediate to 12 min, with the PAPE magnitude later verified by one or multiple verification tests. However, when a control group is established, the recovery time may be extended to 20 min.

In practice, we recommend that three sets of five repetitions of plyometric exercise are prioritized, followed by a recovery time of 5.5 min. We recommend that the number of sets, repetitions, recovery time between sets, and recovery time after plyometric exercise are then adjusted according to the athlete's response, to achieve the optimal PAPE magnitude. However, it is important to note that the current results are biased owing to publication bias. Therefore, these values should be considered as reference points for similar settings, rather than applicable to all athletes.

5 Conclusions

The results of the current meta-analysis reveal that the overall effect of PAPE on athletic performance compared with a control group or condition is small. Specifically, PAPE had a small effect on jump, upper body, and sprint performances and a moderate effect on agility. However, control group performances, on average, decreased over time, possibly because of reductions in muscle temperature or motivation over the control period, which increased the resulting effect of a CA. The effect of a comprehensive GW was similar to that of a non-comprehensive GW in the PAPE versus control group comparisons, which may partly result from the control group reducing performance alongside any performance enhancement from the CA itself. When the experimental group data were analyzed independently, CAs had only a trivial overall impact on performance. Additionally, both the GW comprehensiveness and duration of Rest-1 (between

GW and baseline testing) influenced PAPE magnitude. In particular, CAs had no detectable effect when performed after a comprehensive GW and short Rest-1 time. When non-comprehensive GWs were performed and thus a PAPE effect was observed, an inverted U-shaped post-CA performance enhancement profile was observed, although effects were also observed within the first minute of CA completion.

It should be highlighted that the majority of PAPE studies suffer from design issues that prevent the differentiation between the effects of GW and PAPE. To address this, we propose a theoretical model with one of the experimental setups designed to minimize GW effects on PAPE. Another experimental setup was designed to determine the effect of GW + CA compared with GW, and to identify the optimal warm-up. Additionally, methodological recommendations for PAPE research have been outlined in this study. These recommendations should guide future studies exploring the role of PAPE in athletic performance.

Supplementary Information The online version contains supplementary material available at <https://doi.org/10.1007/s40279-024-02170-6>.

Acknowledgements We thank KongYun Huang, WengXinNan Ma, HuaKun Zheng, and HengHao Yan for evaluating the comprehensiveness of the general warm-up.

Declarations

Funding This project was funded by Shanghai Commission of Science and Technology (21010503500).

Ethics approval Not applicable.

Consent to participate Not applicable.

Code availability Not applicable.

Conflict of interest Kai Xu, Anthony J. Blazevich, Daniel Boullosa, Rodrigo Ramirez-Campillo, MingYue Yin, YuMing Zhong, Yuhang Tian, Mitchell Finlay, Paul J. Byrne, Francisco Cuenca-Fernández, and Ran Wang declare that they have no conflicts of interest relevant to the content of this project.

Availability of data and material The datasets generated and/or analyzed during the current review are available in tables, supplementary files, and at the Open Science Framework (osf.io/v7sbt). All other data are available upon request.

Author contributions K.X. performed all the analyses, visualized the data, and wrote the first draft of the manuscript. All authors edited and revised the manuscript and approved the final version of the manuscript.

References

- Bishop D. Warm up II: performance changes following active warm up and how to structure the warm up. *Sports Med.* 2003;33:483–98.

2. Bishop D. Warm up I: potential mechanisms and the effects of passive warm up on exercise performance. *Sports Med.* 2003;33:439–54.
3. Afonso J, Brito J, Abade E, Rendeiro-Pinho G, Baptista I, Figueiredo P, et al. Revisiting the ‘whys’ and ‘hows’ of the warm-up: are we asking the right questions? *Sports Med.* 2024;54(1):23–30. <https://doi.org/10.1007/s40279-023-01908-y>.
4. Jeffreys I. Warm up revisited—the ‘ramp’ method of optimising performance preparation. *UKSCA J.* 2006;6:15–9.
5. McGowan CJ, Pyne DB, Thompson KG, Ratray B. Warm-up strategies for sport and exercise: mechanisms and applications. *Sports Med.* 2015;45:1523–46.
6. Silva LM, Neiva HP, Marques MC, Izquierdo M, Marinho DA. Effects of warm-up, post-warm-up, and re-warm-up strategies on explosive efforts in team sports: a systematic review. *Sports Med.* 2018;48:2285–99.
7. 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.
8. Healy R, Comyns TM. The application of postactivation potentiation methods to improve sprint speed. *Strength Cond J.* 2017;39(1):1–9.
9. 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.
10. 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(9):1559–65.
11. Rassier D, Macintosh B. Coexistence of potentiation and fatigue in skeletal muscle. *Braz J Med Biol Res Revista brasileira de pesquisas médicas e biológicas / Sociedade Brasileira de Biofísica [et al].* 2000;33:499–508. <https://doi.org/10.1590/S0100-879X2000000500003>.
12. Vandendoolboom R. Modulation of skeletal muscle contraction by myosin phosphorylation. *Compr Physiol.* 2017;7:171–212. <https://doi.org/10.1002/cphy.c150044>.
13. Sale DG. Postactivation potentiation: role in human performance. *Exerc Sport Sci Rev.* 2002;30(3):138–43.
14. Sale D. Postactivation potentiation: role in performance. *Br J Sports Med.* 2004;38(4):386–7.
15. Tillin NA, Bishop D. Factors modulating post-activation potentiation and its effect on performance of subsequent explosive activities. *Sports Med.* 2009;39:147–66.
16. Classen J, Liepert J, Wise SP, Hallett M, Cohen LG. Rapid plasticity of human cortical movement representation induced by practice. *J Neurophysiol.* 1998;79(2):1117–23.
17. Gottschall JS, Palmer BM. The acute effects of prior cycling cadence on running performance and kinematics. *Med Sci Sports Exerc.* 2002;34(9):1518–22.
18. Koedijker JM, Oudejans RR, Beek PJ. Interference effects in learning similar sequences of discrete movements. *J Mot Behav.* 2010;42(4):209–22.
19. Boullosa D. Post-activation performance enhancement strategies in sport: a brief review for practitioners. *Hum Mov.* 2021;22(3):101–9.
20. Wilson JM, Duncan NM, Marin PJ, Brown LE, Loenneke JP, Wilson SM, et al. Meta-analysis of postactivation potentiation and power: effects of conditioning activity, volume, gender, rest periods, and training status. *J Strength Cond Res.* 2013;27(3):854–9.
21. Suchomel TJ, Lamont HS, Moir GL. Understanding vertical jump potentiation: a deterministic model. *Sports Med.* 2016;46:809–28.
22. Anthi X, Dimitrios P, Christos K. On the mechanisms of post-activation potentiation: the contribution of neural factors. *J Phys Educ Sport.* 2014;14(2):134.
23. Singh AM, Staines WR. The effects of acute aerobic exercise on the primary motor cortex. *J Mot Behav.* 2015;47(4):328–39.
24. 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(1):e1–7.
25. Maloney SJ, Turner AN, Fletcher IM. Ballistic exercise as a pre-activation stimulus: a review of the literature and practical applications. *Sports Med.* 2014;44:1347–59.
26. Boullosa D, Beato M, Iacono AD, Cuenca-Fernández F, Doma K, Schumann M, et al. A new taxonomy for postactivation potentiation in sport. *Int J Sports Physiol Perform.* 2020;15(8):1197–200.
27. Krzysztofik M, Wilk M, Stastny P, Golas A. Post-activation performance enhancement in the bench press throw: a systematic review and meta-analysis. *Front Physiol.* 2021;11: 598628.
28. Finlay MJ, Bridge CA, Greig M, Page RM. Upper-body post-activation performance enhancement for athletic performance: a systematic review with meta-analysis and recommendations for future research. *Sports Med.* 2022;52(4):847–71.
29. Mola JN, Bruce-Low SS, Burnet SJ. Optimal recovery time for postactivation potentiation in professional soccer players. *J Strength Cond Res.* 2014;28(6):1529–37. <https://doi.org/10.1519/jsc.0000000000000313>.
30. Till KA, Cooke C. The effects of postactivation potentiation on sprint and jump performance of male academy soccer players. *J Strength Cond Res.* 2009;23(7):1960–7. <https://doi.org/10.1519/JSC.0b013e3181b8666e>.
31. Fletcher IM. An investigation into the effect of a pre-performance strategy on jump performance. *J Strength Cond Res.* 2013;27(1):107–15. <https://doi.org/10.1519/JSC.0b013e3182517ffb>.
32. Van den Noortgate W, López-López JA, Marín-Martínez F, Sánchez-Meca J. Three-level meta-analysis of dependent effect sizes. *Behav Res Methods.* 2013;45:576–94.
33. Krčmár M, Šimonek J, Vasiľovský I. The acute effect of lower-body training on average power output measured by loaded half-squat jump exercise. *Acta Gymnica.* 2015;45(3):103–11. <https://doi.org/10.5507/ag.2015.016>.
34. Boullosa D, Del Rosso S, Behm DG, Foster C. Post-activation potentiation (PAP) in endurance sports: a review. *Eur J Sports Sci.* 2018;18(5):595–610. <https://doi.org/10.1080/17461391.2018.1438519>.
35. MacIntosh BR, Robillard M-E, Tomaras EK. Should postactivation potentiation be the goal of your warm-up? *Appl Physiol Nutr Metab.* 2012;37(3):546–50.
36. Vasconcelos GC, Brietzke C, Cesario JCS, Douetts CDB, Canestri R, Vinicius Í, et al. No evidence of postactivation performance enhancement on endurance exercises: a comprehensive systematic review and meta-analysis. *Med Sci Sports Exerc.* 2024;56(2):315–27. <https://doi.org/10.1249/mss.0000000000000308>.
37. Singh U, Connor JD, Leicht AS, Brice SM, Doma K. Acute effects of prior conditioning activity on change of direction performance. A systematic review and meta-analysis. *J Sports Sci.* 2023;41(18):1701–17. <https://doi.org/10.1080/02640414.2023.2293556>.
38. Gouveia AL, Fernandes IA, Cesar EP, Silva WAB, Gomes PSC. The effects of rest intervals on jumping performance: a meta-analysis on post-activation potentiation studies. *J Sports Sci.* 2013;31(5):459–67.
39. Dobbs WC, Tolusso DV, Fedewa MV, Esco MR. Effect of postactivation potentiation on explosive vertical jump: a

- systematic review and meta-analysis. *J Strength Cond Res*. 2019;33(7):2009–18.
40. Kadlec D, Sainani KL, Nimpfius S. With great power comes great responsibility: common errors in meta-analyses and meta-regressions in strength & conditioning research. *Sports Med*. 2023;53(2):313–25.
 41. Abade E, Brito J, Gonçalves B, Saura L, Coutinho D, Sampaio J. Using deadlifts as a postactivation performance enhancement strategy in warm-ups in football. *J Strength Cond Res*. 2023;37(9):1821–7. <https://doi.org/10.1519/jsc.00000000000004485>.
 42. Barreto MVC, Telles J, de Castro MR, Mendes TT, Rodrigues CP, de Freitas VH. Temporal response of post-activation performance enhancement induced by a plyometric conditioning activity. *Front Sports Active Living*. 2023;5:1209960. <https://doi.org/10.3389/fspor.2023.1209960>.
 43. 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(1):68–73. <https://doi.org/10.1519/jsc.00000000000004243>.
 44. Biel P, Zubik M, Filip-Stachnik A, Ewertowska P, Krzysztofik M. Acute effects of unilateral and bilateral conditioning activity on countermovement jump, linear speed, and muscle stiffness: a randomized crossover study. *PLoS ONE*. 2023;18(10): e0292999. <https://doi.org/10.1371/journal.pone.0292999>.
 45. Fu K, Chen L, Poon ET, Wang R, Li Q, Liu H, et al. Postactivation performance enhancement of flywheel training on lower limb explosive power performance. *Front Physiol*. 2023;14:1217045. <https://doi.org/10.3389/fphys.2023.1217045>.
 46. Jiang X, Li X, Xu Y, Sun D, Baker JS, Gu Y. Can PAPE-induced increases in jump height be explained by jumping kinematics? *Mol Cell Biomech*. 2023;20(2):67–79. <https://doi.org/10.32604/mcb.2023.042910>.
 47. Koźlenia D, Domaradzki J. postsubmaximal isometric full squat jump potentiation in trained men. *J Strength Cond Res*. 2023. <https://doi.org/10.1519/jsc.00000000000004647>.
 48. 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(7):1486–94. <https://doi.org/10.1519/jsc.00000000000004404>.
 49. 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(7):1397–403. <https://doi.org/10.1519/jsc.00000000000004398>.
 50. Yeh TY, Wimmenauer HM, Lamont HS, Smith JC. Acute effect of heavy load back squat and foam rolling on vertical jump performance. *Res Quart Exerc Sport*. 2023. <https://doi.org/10.1080/02701367.2023.2230282>.
 51. Zisi M, Stavridis I, Bogdanis G, Terzis G, Paradisis G. The acute effects of plyometric exercises on sprint performance and kinematics. *Physiologia*. 2023;3(2):295–304.
 52. Finlay MJ, Greig M, Bridge CA, Page RM. Post-activation performance enhancement of punch force and neuromuscular performance in amateur boxing: toward a more individualized and “real-world” approach. *J Strength Cond Res*. 2024. <https://doi.org/10.1519/jsc.00000000000004740>.
 53. Kannas TM, Chalatzoglou G, Arvanitidou E, Babault N, Paizis C, Arabatzi F. Evaluating the efficacy of eccentric half-squats for post-activation performance enhancement in jump ability in male jumpers. *Appl Sci*. 2024;14(2):749.
 54. Zheng Z, Wang Y, Wei H, et al. Effects of external limb compression and/or low-load resistance exercise on post-activation performance enhancement during countermovement jumps. *Eur J Sport Sci*. 2024;24(2):249–58. <https://doi.org/10.1002/ejsc.12064>.
 55. Brink NJ, Constantinou D, Torres G. Postactivation performance enhancement in healthy adults using a bodyweight conditioning activity: a systematic review and meta-analysis. *J Strength Cond Res*. 2023;37(4):930–7.
 56. Page MJ, McKenzie JE, Bossuyt PM, Boutron I, Hoffmann TC, Mulrow CD, et al. The PRISMA 2020 statement: an updated guideline for reporting systematic reviews. *Int J Surg*. 2021;88: 105906.
 57. Drevon D, Fursa SR, Malcolm AL. Intercoder reliability and validity of WebPlotDigitizer in extracting graphed data. *Behav Modif*. 2017;41(2):323–39.
 58. French DN, Kraemer WJ, Cooke CB. Changes in dynamic exercise performance following a sequence of preconditioning isometric muscle actions. *J Strength Cond Res*. 2003;17(4):678–85. [https://doi.org/10.1519/1533-4287\(2003\)017%3c0678:cidepf%3e2.0.co;2](https://doi.org/10.1519/1533-4287(2003)017%3c0678:cidepf%3e2.0.co;2).
 59. Saez de Villarreal ES, González-Badillo JJ, Izquierdo M, Saez Saez de Villarreal E, González-Badillo JJ. Optimal warm-up stimuli of muscle activation to enhance short and long-term acute jumping performance. *Eur J Appl Physiol*. 2007;100(4):393–401.
 60. Markovic G, Simek S, Bradic A. Are acute effects of maximal dynamic contractions on upper-body ballistic performance load specific? *J Strength Cond Res*. 2008;22(6):1811–5. <https://doi.org/10.1519/JSC.0b013e318182227e>.
 61. Arabatzi F, Patikas D, Zafeiridis A, Giavroudis K, Kannas T, Gourgoulis V, et al. The post-activation potentiation effect on squat jump performance: age and sex effect. *Pediatr Exerc Sci*. 2014;26(2):187–94. <https://doi.org/10.1123/pes.2013-0052>.
 62. Hirayama K. Acute effects of an ascending intensity squat protocol on vertical jump performance. *J Strength Cond Res*. 2014;28(5):1284–8. <https://doi.org/10.1519/jsc.000000000000000259>.
 63. Turner AP, Bellhouse S, Kilduff LP, Russell M. Postactivation potentiation of sprint acceleration performance using plyometric exercise. *J Strength Cond Res*. 2015;29(2):343–50. <https://doi.org/10.1519/jsc.0000000000000647>.
 64. 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(4):625–32.
 65. Arias JC, Coburn JW, Brown LE, Galpin AJ. The acute effects of heavy deadlifts on vertical jump performance in men. *Sports (Basel)*. 2016. <https://doi.org/10.3390/sports4020022>.
 66. Piper AD, Joubert DP, Jones EJ, Whitehead MT. Comparison of post-activation potentiating stimuli on jump and sprint performance. *Int J Exerc Sci*. 2020;13(4):539–53.
 67. Krzysztofik M, Trybulski R, Trąbka B, Perenc D, Łuszcz K, Zajac A, et al. The impact of resistance exercise range of motion on the magnitude of upper-body post-activation performance enhancement. *BMC Sports Sci Med Rehabil*. 2022;14(1):123. <https://doi.org/10.1186/s13102-022-00519-w>.
 68. Spieszny M, Trybulski R, Biel P, Zajac A, Krzysztofik M. Post-isometric back squat performance enhancement of squat and countermovement jump. *Int J Environ Res Public Health*. 2022. <https://doi.org/10.3390/ijerph191912720>.
 69. Brandenburg JP. The acute effects of prior dynamic resistance exercise using different loads on subsequent upper-body explosive performance in resistance-trained men. *J Strength Cond Res*. 2005;19(2):427–32. <https://doi.org/10.1519/r-15074.1>.
 70. Reardon D, Hoffman JR, Mangine GT, Wells AJ, Gonzalez AM, Jajtner AR, et al. Do changes in muscle architecture affect post-activation potentiation? *J Sports Sci Med*. 2014;13(3):483–92.
 71. Chaouachi A, Poulos N, Abed F, Turki O, Brughelli M, Chamari K, et al. Volume, intensity, and timing of muscle

- power potentiation are variable. *Appl Physiol Nutr Metab.* 2011;36(5):736–47. <https://doi.org/10.1139/H11-079>.
72. Silberzahn R, Uhlmann EL, Martin DP, Anselmi P, Aust F, Awtrey E, et al. Many analysts, one data set: making transparent how variations in analytic choices affect results. *Adv Methods Pract Psychol Sci.* 2018;1(3):337–56.
 73. Hedges LV, Olkin I. Statistical methods for meta-analysis. New York: Academic Press; 2014.
 74. Ellington WR. Evolution and physiological roles of phosphagen systems. *Annu Rev Physiol.* 2001;63(1):289–325.
 75. Galazoulas C, Tzimou A, Karamousalidis G, Mougios V. Gradual decline in performance and changes in biochemical parameters of basketball players while resting after warm-up. *Eur J Appl Physiol.* 2012;112:3327–34.
 76. McKay AKA, Stellingwerff T, Smith ES, Martin DT, Mujika I, Goosey-Tolfrey VL, et al. Defining training and performance caliber: a participant classification framework. *Int J Sports Physiol Perform.* 2022;17(2):317–31. <https://doi.org/10.1123/ijssp.2021-0451>.
 77. Higgins JP, Altman DG, Gøtzsche PC, Jüni P, Moher D, Oxman AD, et al. The Cochrane collaboration's tool for assessing risk of bias in randomised trials. *Br Med J.* 2011;343:d5928. <https://doi.org/10.1136/bmj.d5928>.
 78. Dello Iacono A, Padulo J, Eliakim A, Gottlieb R, Bareli R, Meckel Y. Post-activation potentiation effects on vertical and horizontal explosive performances of young handball and basketball athletes. *J Sports Med Phys Fit.* 2016;56(12):1455–64.
 79. Zimmermann HB, Knihs D, Diefenthäler F, MacIntosh B, Dal Pupo J. Continuous jumps enhance twitch peak torque and sprint performance in highly trained sprint athletes. *Int J Sports Physiol Perform.* 2021;16(4):565–72. <https://doi.org/10.1123/ijssp.2020-0240>.
 80. Brughelli M, Cronin J, Levin G, Chaouachi A. Understanding change of direction ability in sport: a review of resistance training studies. *Sports Med.* 2008;38:1045–63.
 81. Becker BJ. Synthesizing standardized mean-change measures. *Br J Math Stat Psychol.* 1988;41(2):257–78.
 82. Morris SB. Estimating effect sizes from pretest–posttest–control group designs. *Organ Res Methods.* 2008;11(2):364–86.
 83. Morris SB, DeShon RP. Combining effect size estimates in meta-analysis with repeated measures and independent-groups designs. *Psychol Methods.* 2002;7(1):105.
 84. Higgins JPT, Thomas J, Chandler J, Cumpston M, Li T, Page MJ, Welch VA, editors. Cochrane handbook for systematic reviews of interventions version 6.5 (updated August 2024). Cochrane. 2024. Available from www.training.cochrane.org/handbook.
 85. Maroto-Izquierdo S, Bautista JJ, Rivera FM. Post-activation performance enhancement (PAPE) after a single bout of high-intensity flywheel resistance training. *Biol Sport.* 2020;37(4):343–50. <https://doi.org/10.5114/BIOLSPORT.2020.96318>.
 86. Cohen J. Statistical power analysis for the behavioral sciences. New York: Academic Press; 2013.
 87. Nagashima K, Noma H, Furukawa TA. Prediction intervals for random-effects meta-analysis: a confidence distribution approach. *Stat Methods Med Res.* 2019;28(6):1689–702.
 88. Harrer M, Cuijpers P, Furukawa T, Ebert D. Doing meta-analysis with R: a hands-on guide. Boca Raton: Chapman and Hall/CRC; 2021.
 89. Herring CH, Goldstein ER, Fukuda DH. Use of tensiomyography in evaluating sex-based differences in resistance-trained individuals after plyometric and isometric midthigh pull postactivation potentiation protocols. *J Strength Cond Res.* 2021;35(6):1527–34. <https://doi.org/10.1519/jsc.00000000000004033>.
 90. Cooper H, Hedges LV, Valentine JC. The handbook of research synthesis and meta-analysis 2nd edition. In: The hand of res synthesis and meta-analysis, 2nd edn. Russell Sage Foundation; 2009. p. 1–615.
 91. Assink M, Wibbelink CJ. Fitting three-level meta-analytic models in R: a step-by-step tutorial. *Quant Methods Psychol.* 2016;12(3):154–74.
 92. Jukic I, Castilla AP, Ramos AG, Van Hooren B, McGuigan MR, Helms ER. The acute and chronic effects of implementing velocity loss thresholds during resistance training: a systematic review, meta-analysis, and critical evaluation of the literature. *Sports Med.* 2023;53(1):177–214.
 93. Cheung MW-L. Modeling dependent effect sizes with three-level meta-analyses: a structural equation modeling approach. *Psychol Methods.* 2014;19(2):211.
 94. Cheung MW-L. A guide to conducting a meta-analysis with non-independent effect sizes. *Neuropsychol Rev.* 2019;29(4):387–96.
 95. Viechtbauer W. Conducting meta-analyses in R with the metafor package. *J Stat Softw.* 2010;36:1–48.
 96. Guggenheimer JD, Dickin DC, Reyes GF, Dolny DG. The effects of specific preconditioning activities on acute sprint performance. *J Strength Cond Res.* 2009;23(4):1135–9. <https://doi.org/10.1519/JSC.0b013e318191892e>.
 97. Harrell FE. Regression modeling strategies: with applications to linear models, logistic regression, and survival analysis. Berlin: Springer; 2001.
 98. Nuzzo JL, Pinto MD, Nosaka K, Steele J. Maximal number of repetitions at percentages of the one repetition maximum: a meta-regression and moderator analysis of sex, age, training status, and exercise. *Sports Med.* 2024;54(2):303–21.
 99. Montgomery DC, Peck EA, Vining GG. Introduction to linear regression analysis. New York: Wiley; 2021.
 100. Cleveland WS, Devlin SJ. Locally weighted regression: an approach to regression analysis by local fitting. *J Am Stat Assoc.* 1988;83(403):596–610.
 101. Wickham H. ggplot2. Wiley Interdiscipl Rev Comput Stat. 2011;3(2):180–5.
 102. Peters JL, Sutton AJ, Jones DR, Abrams KR, Rushton L. Contour-enhanced meta-analysis funnel plots help distinguish publication bias from other causes of asymmetry. *J Clin Epidemiol.* 2008;61(10):991–6.
 103. Egger M, Smith GD, Schneider M, Minder C. Bias in meta-analysis detected by a simple, graphical test. *BMJ.* 1997;315(7109):629–34.
 104. Afonso J, Ramirez-Campillo R, Clemente FM, Büttner FC, Andrade R. The perils of misinterpreting and misusing “publication bias” in meta-analyses: an education review on funnel plot-based methods. *Sports Med.* 2023. <https://doi.org/10.1007/s40279-023-01927-9>.
 105. Viechtbauer W, Cheung MWL. Outlier and influence diagnostics for meta-analysis. *Res Synth Methods.* 2010;1(2):112–25.
 106. Ling RF. Residuals and influence in regression. Abingdon: Taylor & Francis; 1984.
 107. Hedges LV, Tipton E, Johnson MC. Robust variance estimation in meta-regression with dependent effect size estimates. *Res Synth Methods.* 2010;1(1):39–65.
 108. Tipton E, Pustejovsky JE. Small-sample adjustments for tests of moderators and model fit using robust variance estimation in meta-regression. *J Educ Behav Stat.* 2015;40(6):604–34.
 109. Schünemann HJ, Higgins JP, Vist GE, Glasziou P, Akl EA, Skoetz N, et al. Completing ‘Summary of findings’ tables and grading the certainty of the evidence. In: Cochrane handbook for systematic reviews of interventions. 2019. p. 375–402. <https://doi.org/10.1002/9781119536604.ch14>.
 110. Guyatt G, Oxman AD, Akl EA, Kunz R, Vist G, Brozek J, et al. GRADE guidelines: 1. Introduction—GRADE evidence profiles and summary of findings tables. *J Clin Epidemiol.* 2011;64(4):383–94.

111. Munro LA, Stannard SR, Fink PW, Foskett A. Potentiation of sprint cycling performance: the effects of a high-inertia ergometer warm-up. *J Sports Sci.* 2017;35(14):1442–50. <https://doi.org/10.1080/02640414.2016.1215492>.
112. Toprak T, Bakici D, Kaymakçı AT, Gelen E. Effects of static and dynamic post-activation potentiation protocols on change of direction performance in adolescent soccer players. *Acta Facultatis Educationis Physicae Universitatis Comenianae.* 2022;62(2):96–108.
113. Lockie R, Davis D, Giuliano D, Risso F, Orjalo A, Moreno M, et al. A preliminary case analysis of the post-activation potentiation effects of plyometrics on sprint performance in women. *Sport Sci Rev.* 2016. <https://doi.org/10.1515/ssr-2016-0016>.
114. Gilbert G, Lees A. Changes in the force development characteristics of muscle following repeated maximum force and power exercise. *Ergonomics.* 2005;48(11–14):1576–84. <https://doi.org/10.1080/00140130500101163>.
115. Matthews M, Matthews H, Snook BEN. The acute effects of a resistance training warmup on sprint performance. *Res Sports Med.* 2004;12(2):151–9.
116. Grimes N, Arede J, Drury B, Thompson S, Fernandes J. The effects of a sled push at different loads on 20 metre sprint time in well-trained soccer players. *Int J Strength Cond.* 2021;1(1). <https://doi.org/10.2174/1875399X01710010097>.
117. Zisi M, Stavridis I, Agilar GO, Economou T, Paradisis G. The acute effects of heavy sled towing on acceleration performance and sprint mechanical and kinematic characteristics. *Sports (Basel).* 2022. <https://doi.org/10.3390/sports10050077>.
118. Finlay MJ, Bridge CA, Greig M, Page RM. Postactivation performance enhancement of amateur boxers' punch force and neuromuscular performance following 2 upper-body conditioning activities. *Int J Sports Physiol Perform.* 2022;17(11):1621–33.
119. Linder EE, Prins JH, Murata NM, Derenne C, Morgan CF, Solomon JR. Effects of preload 4 repetition maximum on 100-m sprint times in collegiate women. *J Strength Cond Res.* 2010;24(5):1184–90. <https://doi.org/10.1519/JSC.0b013e3181d75806>.
120. Batista MA, Roschel H, Barroso R, Ugrinowitsch C, Tricoli V. Influence of strength training background on postactivation potentiation response. *J Strength Cond Res.* 2011;25(9):2496–502. <https://doi.org/10.1519/JSC.0b013e318200181b>.
121. Lima JCB, Marin DP, Barquilha G, Da Silva LO, Puggina EF, Pithon-Curi TC, et al. Acute effects of drop jump potentiation protocol on sprint and counter movement vertical jump performance. *Hum Mov.* 2011;12(4):324–30.
122. Crum AJ, Kawamori N, Stone MH, Haff GG. The acute effects of moderately loaded concentric-only quarter squats on vertical jump performance. *J Strength Cond Res.* 2012;26(4):914–25. <https://doi.org/10.1519/JSC.0b013e318248d79c>.
123. Margaritopoulos S, Theodorou A, Methenitis S, Zaras N, Donti O, Tsolakis C. The effect of plyometric exercises on repeated strength and power performance in elite karate athletes. *J Phys Educ Sport.* 2015;15(2):310–8. <https://doi.org/10.7752/jpes.2015.02047>.
124. Wyland TP, Van Dorin JD, Reyes GF. Postactivation potentiation effects from accommodating resistance combined with heavy back squats on short sprint performance. *J Strength Cond Res.* 2015;29(11):3115–23. <https://doi.org/10.1519/jsc.00000000000000991>.
125. Ong JH, Lim J, Chong E, Tan F. The effects of eccentric conditioning stimuli on subsequent counter-movement jump performance. *J Strength Cond Res.* 2016;30(3):747–54. <https://doi.org/10.1519/jsc.0000000000001154>.
126. Vanderka M, Krčmár M, Longová K, Walker S. Acute effects of loaded half-squat jumps on sprint running speed in track and field athletes and soccer players. *J Strength Cond Res.* 2016;30(6):1540–6. <https://doi.org/10.1519/jsc.0000000000001259>.
127. Abade E, Sampaio J, Gonçalves B, Baptista J, Alves A, Viana J. Effects of different re-warm up activities in football players' performance. *PLoS ONE.* 2017;12(6): e0180152. <https://doi.org/10.1371/journal.pone.0180152>.
128. Lockie RG, Lazar A, Risso FG, Giuliano DV, Liu TM, Stage AA, et al. Limited post-activation potentiation effects provided by the walking lunge on sprint acceleration: a preliminary analysis. *Open Sports Sci J.* 2017;10(1). <https://doi.org/10.2174/1875399X01710010097>.
129. Smilios I, Sotiropoulos K, Barzouka K, Christou M, Tokmakidis SP. Contrast loading increases upper body power output in junior volleyball athletes. *Pediatr Exerc Sci.* 2017;29(1):103–8. <https://doi.org/10.1123/pes.2016-0095>.
130. Lockie RG, Orjalo A, Moreno M. A pilot analysis: can the Bulgarian split-squat potentiate sprint acceleration in strength-trained men? *Facta Universitatis Ser Phys Educ Sport.* 2018;15(3):453–66.
131. Krzysztofik M, Wilk M. The effects of plyometric conditioning on post-activation bench press performance. *J Hum Kinet.* 2020;74:99–108. <https://doi.org/10.2478/hukin-2020-0017>.
132. Orjalo AJ, Lockie RG, Balfany K, Callaghan SJ. The effects of lateral bounds on post-activation potentiation of change-of-direction speed measured by the 505 test in college-aged men and women. *Sports (Basel).* 2020. <https://doi.org/10.3390/sport8050071>.
133. Thapa RK, Kumar A, Kumar G, Narvariya P. A combination of ballistic exercises with slow and fast stretch-shortening cycle induces post-activation performance enhancement. *Trends Sport Sci.* 2020;27(4):203–11. <https://doi.org/10.23829/TSS.2020.27.4-3>.
134. Villalon-Gasch L, Jimenez-Olmedo JM, Sebastian-Amat S, Pueo B. Squat-based post-activation potentiation improves the vertical jump of elite female volleyball players. *J Phys Educ Sport.* 2020;20(4):1950–6. <https://doi.org/10.7752/jpes.2020.04264>.
135. do Carmo EC, De Souza EO, Roschel H, Kobal R, Ramos H, Gil S, et al. Self-selected rest interval improves vertical jump post-activation potentiation. *J Strength Cond Res.* 2021;35(1):91–6. <https://doi.org/10.1519/jsc.0000000000002519>.
136. Krčmár M, Krčmárová B, Bakaří I, Šimonek J. Acute performance enhancement following squats combined with elastic bands on short sprint and vertical jump height in female athletes. *J Strength Cond Res.* 2021;35(2):318–24. <https://doi.org/10.1519/jsc.0000000000003881>.
137. Krzysztofik M, Kalinowski R, Trybulski R, Filip-Stachnik A, Stastny P. Enhancement of countermovement jump performance using a heavy load with velocity-loss repetition control in female volleyball players. *Int J Environ Res Public Health.* 2021. <https://doi.org/10.3390/ijerph182111530>.
138. Marin DP, Astorino TA, Serafim AIS, Urtado CB, Prestes J, Polito LFT, et al. Comparison between traditional resistance exercise and variable resistance with elastic bands in acute vertical jump performance. *Hum Mov.* 2021;22(4):28–35. <https://doi.org/10.5114/hm.2021.103287>.
139. Sener T, Sozbır K, Karlı U. Acute effects of plyometric warm-up with different box heights on sprint and agility performance in national-level field hockey athletes. *Isokinetic Exerc Sci.* 2021;29(1):1–9. <https://doi.org/10.3233/IES-203127>.
140. Downey RJ, Deprez DA, Chilibeck PD. Effects of postactivation potentiation on maximal vertical jump performance after a conditioning contraction in upper-body and lower-body muscle groups. *J Strength Cond Res.* 2022;36(1):259–61. <https://doi.org/10.1519/jsc.0000000000004171>.
141. Filip-Stachnik A, Spieszny M, Stanisz L, Krzysztofik M. Does caffeine ingestion affect the lower-body post-activation

- performance enhancement in female volleyball players? *BMC Sports Sci Med Rehabil.* 2022;14(1):93. <https://doi.org/10.1186/s13102-022-00488-0>.
142. Trybulski R, Makar P, Alexe DI, Stanciu S, Piwowar R, Wilk M, et al. Post-activation performance enhancement: save time with active intra-complex recovery intervals. *Front Physiol.* 2022;13: 840722. <https://doi.org/10.3389/fphys.2022.840722>.
 143. Slack MK, Draugalis JR Jr. Establishing the internal and external validity of experimental studies. *Am J Health Syst Pharm.* 2001;58(22):2173–81.
 144. Godwin M, Ruhland L, Casson I, MacDonald S, Delva D, Birtwhistle R, et al. Pragmatic controlled clinical trials in primary care: the struggle between external and internal validity. *BMC Med Res Methodol.* 2003;3:1–7.
 145. Blazevich AJ, Gill ND, Kvorning T, Kay AD, Goh AG, Hilton B, et al. No effect of muscle stretching within a full, dynamic warm-up on athletic performance. *Med Sci Sports Exerc.* 2018;50(6):1258–66. <https://doi.org/10.1249/mss.00000000000001539>.
 146. Comyns TM, Harrison AJ, Hennessy LK. Effect of squatting on sprinting performance and repeated exposure to complex training in male rugby players. *J Strength Cond Res.* 2010;24(3):610–8.
 147. Hopkins WG, Schabort EJ, Hawley JA. Reliability of power in physical performance tests. *Sports Med.* 2001;31:211–34.
 148. Hodgson M, Docherty D, Robbins D. Post-activation potentiation: underlying physiology and implications for motor performance. *Sports Med.* 2005;35:585–95.
 149. Robbins DW. Postactivation potentiation and its practical applicability. *J Strength Cond Res.* 2005;19(2):453–8.
 150. Hopkins WG. How to interpret changes in an athletic performance test. *Sportscience.* 2004;8:1–7.
 151. Borg DN, Barnett AG, Caldwell AR, White NM, Stewart IB. The bias for statistical significance in sport and exercise medicine. *J Sci Med Sport.* 2023;26(3):164–8.
 152. McMahon S, Jenkins D. Factors affecting the rate of phosphocreatine resynthesis following intense exercise. *Sports Med.* 2002;32:761–84.
 153. Jones AM, Wilkerson DP, Berger NJ, Fulford J. Influence of endurance training on muscle [PCr] kinetics during high-intensity exercise. *Am J Physiol-Regul Integr Comp Physiol.* 2007;293(1):R392–401. <https://doi.org/10.1152/ajpregu.00056.2007>.
 154. Hopkins WG. Measures of reliability in sports medicine and science. *Sports Med.* 2000;30:1–15.
 155. Scott SL, Docherty D. Acute effects of heavy preloading on vertical and horizontal jump performance. *J Strength Cond Res.* 2004;18(2):201–5.
 156. Ayala V, Martínez-Bebia M, Latorre JA, Giménez-Blasi N, Jiménez-Casquet MJ, Conde-Pipo J, et al. Influence of circadian rhythms on sports performance. *Chronobiol Int.* 2021;38(11):1522–36.
 157. Koo TK, Li MY. A guideline of selecting and reporting intraclass correlation coefficients for reliability research. *J Chiropr Med.* 2016;15(2):155–63.
 158. Eken Ö, Mainer-Pardos E, Yagin FH, Eken I, Prieto-González P, Nobari H. Motoric performance variation from morning to evening: 80% intensity post-activation potentiation protocol impacts performance and its diurnal amplitude in basketball players. *Front Psychol.* 2022;13:1066026.
 159. Asmussen E, Boje O. Body temperature and capacity for work. *Acta Physiol Scand.* 1945;10(1):1–22.
 160. Racinais S, Oksa J. Temperature and neuromuscular function. *Scand J Med Sci Sports.* 2010;20:1–18.
 161. Scott DJ, Ditroilo M, Marshall PA. Complex training: the effect of exercise selection and training status on postactivation potentiation in rugby league players. *J Strength Cond Res.* 2017;31(10):2694–703.
 162. Cook CJ, Kilduff LP, Crewther BT. Basal and stress-induced salivary testosterone variation across the menstrual cycle and linkage to motivation and muscle power. *Scand J Med Sci Sports.* 2018;28(4):1345–53.
 163. Lachin JM, Foulkes MA. Evaluation of sample size and power for analyses of survival with allowance for nonuniform patient entry, losses to follow-up, noncompliance, and stratification. *Biometrics.* 1986;42(3):507–19. <https://doi.org/10.2307/2531201>.
 164. GÜLICH A, SCHMIDTBLEICHER D. MVC-induced short-term potentiation of explosive force. *New Stud Athl.* 1996;11:67–84.
 165. Laine C, Horton R, DeAngelis CD, Drazen JM, Frizelle FA, Godlee F, et al. Clinical trial registration: looking back and moving ahead. *Lancet.* 2007;369(9577):1909–11.
 166. Rappelt L, Held S, Wiedenmann T, Micke F, Donath L. Post-activation performance enhancement (PAPE) protocols do not further increase jumping performance beyond warm-up effects: findings from three acute randomized crossover trials. *Front Physiol.* 2024. <https://doi.org/10.3389/fphys.2024.1447421>.
 167. Tsurubami R, Oba K, Samukawa M, Takizawa K, Chiba I, Yamanaka M, et al. Warm-up intensity and time course effects on jump performance. *J Sports Sci Med.* 2020;19(4):714.
 168. Andrade DC, Henriquez-Olguin C, Beltran AR, Ramirez MA, Labarca C, Cornejo M, et al. Effects of general, specific and combined warm-up on explosive muscular performance. *Biol Sport.* 2015;32(2):123–8.
 169. Chen Y, Su Q, Yang J, Li G, Zhang S, Lv Y, et al. Effects of rest interval and training intensity on jumping performance: a systematic review and meta-analysis investigating post-activation performance enhancement. *Front Physiol.* 2023;14:1202789.
 170. de Oliveira JJ, Crisp AH, Barbosa CGR, e Silva AdS, Baganha RJ, Verlengia R. Effect of postactivation potentiation on short sprint performance: a systematic review and meta-analysis. *Asian J Sports Med.* 2017;8(4):e14566. <https://doi.org/10.5812/asjms.14566>.
 171. Chen X, Zhang W, He J, Li D, Xie H, Zhou Y, et al. Meta-analysis of the intermittent time of post-activation potentiation enhancement on sprint ability. *J Sports Med Phys Fit.* 2022;63(1):86–94. <https://doi.org/10.23736/s0022-4707.22.13502-4>.
 172. Kiens B, Saltin B, WallØSe L, Wesche J. Temporal relationship between blood flow changes and release of ions and metabolites from muscles upon single weak contractions. *Acta Physiol Scand.* 1989;136(4):551–9.
 173. Thapa RK, Weldon A, Freitas TT, Boullosa D, Afonso J, Granacher U, et al. What do we know about complex-contrast training? A systematic scoping review. *Sports Med Open.* 2024;10(1):104. <https://doi.org/10.1186/s40798-024-00771-z>.
 174. Rixon KP, Lamont HS, Bemben MG. Influence of type of muscle contraction, gender, and lifting experience on post-activation potentiation performance. *J Strength Cond Res.* 2007;21(2):500–5.
 175. Ajemian R, D'Ausilio A, Moorman H, Bizzi E. Why professional athletes need a prolonged period of warm-up and other peculiarities of human motor learning. *J Mot Behav.* 2010;42(6):381–8.
 176. DeRenne C. Effects of postactivation potentiation warm-up in male and female sport performances: a brief review. *Strength Cond J.* 2010;32(6):58–64.
 177. Ryschon T, Fowler M, Wysong R, Anthony A-R, Balaban R. Efficiency of human skeletal muscle in vivo: comparison of isometric, concentric, and eccentric muscle action. *J Appl Physiol.* 1997;83(3):867–74.
 178. de Poli RAB, Boullosa DA, Malta ES, Behm D, Lopes VHF, Barbieri FA, et al. Cycling performance enhancement after drop jumps may be attributed to postactivation potentiation and increased anaerobic capacity. *J Strength Cond Res.*

- 2020;34(9):2465–75. <https://doi.org/10.1519/jsc.0000000000003399>.
179. Zagatto AM, Dutra YM, Claus G, Malta ES, de Poli RAB, Brisola GMP, et al. Drop jumps improve repeated sprint ability performance in professional basketball players. *Biol Sport*. 2022;39(1):59–66. <https://doi.org/10.5114/biolsport.2021.101128>.
180. Docherty D, Hodgson MJ. The application of postactivation potentiation to elite sport. *Int J Sports Physiol Perform*. 2007;2(4):439–44.
181. Simic L, Sarabon N, Markovic G. Does pre-exercise static stretching inhibit maximal muscular performance? A meta-analytical review. *Scand J Med Sci Sports*. 2013;23(2):131–48.
182. McCrary JM, Ackermann BJ, Halaki M. A systematic review of the effects of upper body warm-up on performance and injury. *Br J Sports Med*. 2015;49(14):935–42. <https://doi.org/10.1136/bjsports-2014-094228>.
183. Russell M, West DJ, Harper LD, Cook CJ, Kilduff LP. Half-time strategies to enhance second-half performance in team-sports players: a review and recommendations. *Sports Med*. 2015;45:353–64.
184. Hammami A, Zois J, Slimani M, Russell M, Bouhel E. The efficacy, and characteristics of, warm-up and re-warm-up practices in soccer players: a systematic review. *J Sports Med Phys Fit*. 2016;58(1–2):135–49.
185. Jeffreys I. A review of post-activation potentiation and its application in strength and conditioning. *Prof Strength Cond*. 2008;12:17–25.
186. Moreno-Pérez V, Hernández-Davó JL, Nakamura F, López-Samanes Á, Jiménez-Reyes P, Fernández-Fernández J, et al. Post-activation performance enhancement of dynamic stretching and heavy load warm-up strategies in elite tennis players. *J Back Musculoskelet Rehabil*. 2021;34(3):413–23.
187. Barreto MVC, Nunes RV, De Castro MR, Mendes TT, De Freitas VH. Acute effects of two different active warm-up strategies on vertical jump and running performance. *J Phys Educ Sport*. 2023;23(9):2486–91.
188. Tomaras EK, MacIntosh BR. Less is more: standard warm-up causes fatigue and less warm-up permits greater cycling power output. *J Appl Physiol*. 2011;111(1):228–35.
189. van den Tillaar R, Lerberg E, von Heimburg E. Comparison of three types of warm-up upon sprint ability in experienced soccer players. *J Sport Health Sci*. 2019;8(6):574–8.
190. Schulz KF, Altman DG, Moher D. CONSORT 2010 statement: updated guidelines for reporting parallel group randomised trials. *J Pharmacol Pharmacother*. 2010;1(2):100–7.

Springer Nature or its licensor (e.g. a society or other partner) holds exclusive rights to this article under a publishing agreement with the author(s) or other rightsholder(s); author self-archiving of the accepted manuscript version of this article is solely governed by the terms of such publishing agreement and applicable law.

Authors and Affiliations

Kai Xu¹ · Anthony J. Blazevich² · Daniel Boullosa^{3,4,5} · Rodrigo Ramirez-Campillo⁶ · MingYue Yin¹ · YuMing Zhong¹ · YuHang Tian¹ · Mitchell Finlay⁷ · Paul J. Byrne⁸ · Francisco Cuenca-Fernández^{9,10} · Ran Wang¹ 

✉ Ran Wang
wangran@sus.edu.cn

- ¹ School of Athletic Performance, Shanghai University of Sport, No. 200, Henren Road, Shanghai 200438, China
- ² School of Medical and Health Sciences, Centre for Human Performance, Edith Cowan University, Joondalup, Australia
- ³ Faculty of Physical Activity and Sports Sciences, Universidad de León, León, Spain
- ⁴ Integrated Institute of Health, Federal University of Mato Grosso do Sul, Campo Grande, Brazil
- ⁵ College of Healthcare Sciences, James Cook University, Townsville, Australia

- ⁶ Faculty of Rehabilitation Sciences, Exercise and Rehabilitation Sciences Institute, School of Physical Therapy, Universidad Andres Bello, 7591538 Santiago, Chile
- ⁷ Sport Department, University Academy 92, Old Trafford, Manchester, UK
- ⁸ Department of Health and Sport Sciences, Southeast Technological University, Kilkenny Road Campus, Carlow, Ireland
- ⁹ Department of Sports and Computer Sciences, Universidad Pablo de Olavide, Seville, Spain
- ¹⁰ Aquatics Lab, Department of Physical Education and Sports, Faculty of Sport Sciences, University of Granada, Ctra. Alfácar SN, 18071 Granada, Spain