Sports Med (2016) 46:231–240
DOI 10.1007/s40279-015-0415-7

SYSTEMATIC REVIEW

Factors Modulating Post-Activation Potentiation of Jump, Sprint, Throw, and Upper-Body Ballistic Performances: A Systematic Review with Meta-Analysis

Laurent B. Seitz[1] · **G. Gregory Haff**[2]

Abstract

Background Although post-activation potentiation (PAP) has been extensively examined following the completion of a conditioning activity (CA), the precise effects on subsequent jump, sprint, throw, and upper-body ballistic performances and the factors modulating these effects have yet to be determined. Moreover, weaker and stronger individuals seem to exhibit different PAP responses; however, how they respond to the different components of a strength–power–potentiation complex remains to be elucidated.

Objectives This meta-analysis determined (1) the effect of performing a CA on subsequent jump, sprint, throw, and upper-body ballistic performances; (2) the influence of different types of CA, squat depths during the CA, rest intervals, volumes of CA, and loads during the CA on PAP; and (3) how individuals of different strength levels respond to these various strength–power–potentiation complex components.

Methods A computerized search was conducted in ADONIS, ERIC, SPORTDiscus, EBSCOhost, Google Scholar, MEDLINE, and PubMed databases up to March 2015. The analysis comprised 47 studies and 135 groups of participants for a total of 1954 participants.

Results The PAP effect is small for jump (effect size [ES] = 0.29), throw (ES = 0.26), and upper-body ballistic (ES = 0.23) performance activities, and moderate for sprint (ES = 0.51) performance activity. A larger PAP effect is observed among stronger individuals and those with more experience in resistance training. Plyometric (ES = 0.47) CAs induce a slightly larger PAP effect than traditional high-intensity (ES = 0.41), traditional moderate-intensity (ES = 0.19), and maximal isometric (ES = –0.09) CAs, and a greater effect after shallower (ES = 0.58) versus deeper (ES = 0.25) squat CAs, longer (ES = 0.44 and 0.49) versus shorter (ES = 0.17) recovery intervals, multiple- (ES = 0.69) versus single- (ES = 0.24) set CAs, and repetition maximum (RM) (ES = 0.51) versus sub-maximal (ES = 0.34) loads during the CA. It is noteworthy that a greater PAP effect can be realized earlier after a plyometric CA than with traditional high- and moderate-intensity CAs. Additionally, shorter recovery intervals, single-set CAs, and RM CAs are more effective at inducing PAP in stronger individuals, while weaker individuals respond better to longer recovery intervals, multiple-set CAs, and sub-maximal CAs. Finally, both weaker and stronger individuals express greater PAP after shallower squat CAs.

Conclusions Performing a CA elicits small PAP effects for jump, throw, and upper-body ballistic performance activities, and a moderate effect for sprint performance activity. The level of potentiation is dependent on the individual's level of strength and resistance training experience, the type of CA, the depth of the squat when this exercise is employed to elicit PAP, the rest period between the CA and subsequent performance, the number of set(s) of the CA, and the type of load used during the CA. Finally, some components of the strength–power–potentiation complex modulate the PAP response of weaker and stronger individuals in a different way.

✉ Laurent B. Seitz
seitzlaurent@gmail.com

[1] Center of Resources, Expertise and Sports Performance-French Rugby League Academy, 1 Avenue Edouard Belin, 31400 Toulouse, France

[2] Centre for Exercise and Sports Sciences Research (CESSR), Edith Cowan University, Joondalup, WA, Australia

Key Points

The post-activation potentiation (PAP) effect is small for jump, throw, and upper-body ballistic performance activities, and is moderate for sprint performance activity.

The PAP effect is larger among stronger individuals and those with more resistance training experience and after shallower squat conditioning activities (CAs), longer recovery intervals, multiple-set CAs, and repetition maximum (RM) CAs. Additionally, a slightly larger effect can be induced after plyometric CAs.

A greater PAP effect can be realized earlier after the completion of a plyometric CA than with traditional high- or moderate-intensity CAs.

When considering strength status, the PAP effect is larger after shorter recovery intervals and single-set and RM CAs among stronger individuals, while longer recovery intervals, multiple-set CAs, and sub-maximal CAs are more effective at inducing PAP in weaker individuals.

Both weaker and stronger individuals express greater PAP effects after shallower squat CAs.

1 Introduction

There is significant practical interest in the idea that the performance of a maximal, or near maximal, muscle contraction (i.e., a conditioning activity [CA]) may increase the strength/power production in subsequent exercise(s), a phenomenon called post-activation potentiation (PAP). This coupling of a CA with a strength/power exercise is often referred to as a strength–power–potentiation complex [1]. Although there is considerable literature advocating the use of a CA to stimulate enhancement in subsequent jump, sprint, throw, and upper-body ballistic performance, conflicting results have been reported regarding the extent of improvement: overall, increases, no changes, and decreases have been observed (for reviews see Tillin and Bishop [2] and Hodgson et al. [3]). Close examination of the literature reveals that increases in muscle performance after a CA depend on the net balance between fatigue and potentiation, which co-exist at varying degrees after the completion of a CA [4]: muscle performance may improve if potentiation dominates and fatigue is reduced, remain unchanged if fatigue and potentiation are at similar levels, or decrease if fatigue dominates. Ultimately, previous work reveals that the balance between fatigue and potentiation is influenced by the characteristics of both the strength–power–potentiation complex and the individual [2]. For example, there is some evidence that suggests the volume and intensity of the CA as well as the rest period between the CA and the subsequent exercise exert an influence on the magnitude of the PAP response [5]. Specifically, greater levels of potentiation are generally observed with multiple sets of CA performed with moderate intensities and with the subsequent exercise performed after 7–10 min of recovery [5]. Additionally, numerous studies have employed different variations of the back squat exercise as CA, mainly by using different squatting depths. One study directly compared the effects of parallel and quarter squats on subsequent jump performance and reported greater levels of potentiation after the parallel squat CA [6]. The authors suggested that the deeper depth of the parallel squat may have stimulated a greater activation of the gluteus maximus, allowing for a greater PAP response to be achieved. On the other hand, it seems likely that a deeper squat would induce higher levels of acute fatigue because of its longer time under tension [7], and thus reduce the ability of the CA to induce PAP. Moreover, studies have used different types of load during the CA with either repetition maximum (RM) loads [8, 9] or sub-maximal loads performed at a given percentage of 1 RM [10, 11]. Given the relationship between fatigue and potentiation, RM loads may induce greater fatigue than sub-maximal loads and therefore reduce the ability to express PAP. However, to the authors' knowledge, there are no studies that have investigated the influence of the type of load used during the CA on the occurrence of PAP. Therefore, further examination regarding the effects of the squat depth of the CA and type of load during the CA on PAP is warranted and this can be achieved with a meta-analysis of the data presented in the current scientific literature examining the PAP phenomenon. Elucidating this would understandably have important practical applications regarding the implementation of strength–power–potentiation complexes.

With respect to the individual's characteristics, recent reports indicate that stronger individuals are able to express greater potentiation levels than their weaker counterparts [12–14]. In addition, it appears that stronger individuals express their greatest PAP effect earlier after completing a heavy CA than do weaker individuals [12, 15]. A plausible explanation for this phenomenon is that stronger individuals may develop fatigue resistance to heavier loads [16, 17], which may affect the balance between fatigue and potentiation post-CA. Ultimately, alterations in the balance between fatigue and potentiation have the ability to alter the magnitude of PAP expressed post-CA [4]. Given the relationship between strength, fatigue, and PAP, it can be postulated that stronger and weaker individuals may respond differently to the different components of a strength–power–potentiation complex. For example, traditional high-intensity CAs, deeper squat CAs, shorter rest intervals, multiple-set CAs, and maximal effort CAs should theoretically impair the ability of weaker individuals to express high levels of potentiation because of their limited capacity to resist fatigue. Hence, with a view to optimize the PAP response of stronger and weaker individuals, there is a need to determine how stronger and weaker individuals respond to the different components of a strength–power–potentiation complex.

2 Objectives

The purposes of this meta-analysis were to determine (1) the effect of performing a CA on subsequent jump, sprint, throw, and upper-body ballistic performances; (2) the influence of different types of CA, squat depths during the CA, rest intervals, volumes of CA, and loads during the CA on PAP (unless specified, the PAP effect refers to the average value for combined jump, throw, upper-body ballistic, and sprint performance activities); and (3) how weaker and stronger individuals respond to these various strength–power–potentiation complex components. The central hypotheses of this investigation are that (1) improvements in jump, sprint, throw, and upper-body ballistic performances would be observed after a CA; (2) different types of CA, squat depths during the CA, rest intervals, volumes of CA, and loads during the CA would elicit different PAP responses; and (3) stronger and weaker individuals would respond differently to these various strength–power–potentiation complex components.

3 Methods

3.1 Literature Search

ADONIS, ERIC, SPORTDiscus, EBSCOhost, Google Scholar, MEDLINE, and PubMed databases were searched until March 2015 for all studies investigating the PAP phenomenon. The search was performed using the following keyword combinations in the English language: ‘postactivation potentiation’, ‘PAP’, ‘conditioning contraction’, and ‘conditioning activity’. Additionally, the reference lists and citations of the selected articles were scanned using Google Scholar to find additional articles. Attempts were also made to contact the authors of the selected articles to request any missing relevant information. The present meta-analysis includes studies that (1) have presented original research data on healthy human participants; and (2) are published in peer-reviewed journals. No age or sex restrictions were imposed during the search stage.

3.2 Inclusion and Exclusion Criteria

Research studies investigating the effects of a CA on subsequent jump, horizontal jump, sprint, throw, and upper-body ballistic performances were the primary focus of the literature search. A total of 217 studies were initially identified for further scrutiny.

The next step was to select studies with respect to their internal validity: (1) instruments with high reliability and validity were used; (2) a pre-performance test was carried out at baseline before the CA; (3) a warm-up was performed prior completing the pre-performance test; (4) the pre- and post-performance tests and the CA were performed during the same testing session; (5) the study measured jump, running sprint, throw, or upper-body ballistic performance; (6) the study did not use any electrically elicited stimuli during the CA; and (7) the study did not use any isokinetic dynamometer during both the performance tests and CA. After critically analyzing the initial studies collected with the above criteria, a cohort of 47 studies was selected (Fig. 1).

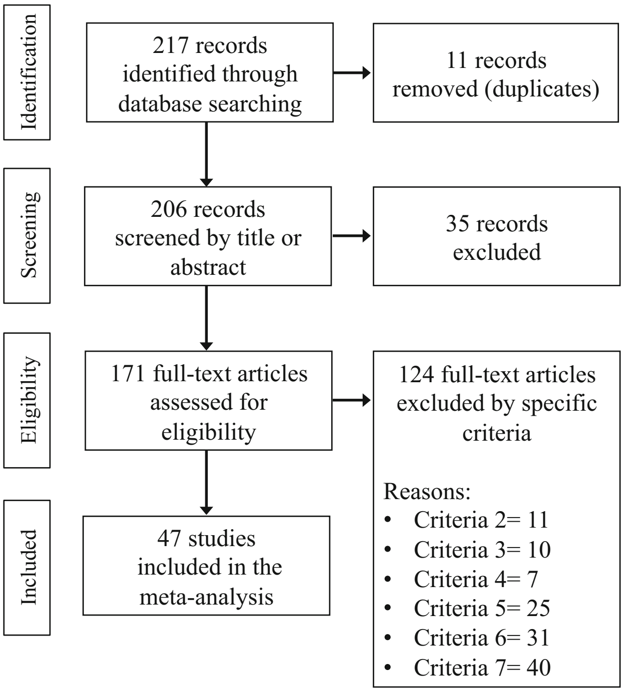

Fig. 1 Flow diagram of the studies that underwent the review process. *Criteria 2* a pre-performance test was carried out at baseline before the CA, *Criteria 3* a warm-up was performed prior completing the pre-performance test, *Criteria 4* the pre- and post-performance tests and the CA were performed during the same testing session, *Criteria 5* the study measured jump, running sprint, throw, or upper-body ballistic performance, *Criteria 6* the study did not use any electrically elicited stimuli during the CA, *Criteria 7* the study did not use any isokinetic dynamometer during both the performance tests and CA. *CA* conditioning activity

3.3 Data Extraction and Quality Assessment

Each study was then read and coded by two independent investigators using different moderator variables. Because PAP can be affected by several variables [2], independent variables were grouped into the following categories: (1) individual's characteristics, including strength level (strong—back squat:body weight ratio $\geq$1.75 and >1.5 for men and women, respectively, and bench press:body weight ratio $\geq$1.35 for men; weak—back squat:body weight ratio <1.75 and $\leq$1.5 for men and women, respectively, and bench press:body weight ratio <1.35 for men) and resistance training experience (none; $\leq$2 years; >2 years); and (2) strength–power–potentiation complex characteristics including the type of CA (traditional high intensity: $\geq$85 % 1 RM; traditional moderate intensity: 30–84 % 1 RM, plyometric, maximal isometric), squat depth when a back squat was used as CA (deep squat: top of the thighs parallel or below parallel; shallow squat: top of the thighs above parallel), recovery interval between the CA and the subsequent performance activity (0.3–4 min; 5–7 min; $\geq$8 min), number of set(s) of CA (single; multiple), and type of load during the CA (RM loads; sub-maximal loads performed at a given percentage of 1 RM). The mean agreement was calculated by an intra-class correlation coefficient (ICC). For such coding methods, a mean agreement of 0.90 is generally accepted as an appropriate level of reliability [18]. A mean agreement of 0.94 was reached in the present investigation, which is well above the 0.90 mark for acceptable reliability. The investigators examined and resolved any coding differences before the final analysis.

3.4 Analysis and Interpretation of Results

Effect sizes (ESs) were used to obtain standardized measurements of the effect of the CA on the outcome variable. The ES is a standardized value that allows the determination of the magnitude of the differences between groups or experimental conditions [19]. The ESs were calculated using Hedges and Olkin's g [18], as follows (Eq. 1) [1]:

$$\mathrm{ES} = g\,\frac{(M_{\mathrm{post}} - M_{\mathrm{pre}})}{\mathrm{SD}_{\mathrm{pooled}}} \tag{1}$$

where M_{post} is the mean of the performance test completed after the CA, M_{pre} is the mean of the performance test completed before the CA, and $\mathrm{SD}_{\mathrm{pooled}}$ is the pooled standard deviation of the measurements (Eq. 2) [2]:

$$\mathrm{SD}_{\mathrm{pooled}} = \frac{((n_1 - 1) \times \mathrm{SD}_1^2 + (n_2 - 1) \times \mathrm{SD}_2^2)}{(n_1 + n_2 - 2)} \tag{2}$$

where SD_1^2 is the standard deviation of the performance test completed before the CA and SD_2^2 is the standard deviation of the performance test completed after the CA.

The should be corrected for the magnitude of sample size of each study because the absolute value of the ES is over-estimated in small sample sizes [18]. Therefore, a correction factor was calculated as follows (Eq. 3) [18]:

$$\text{Correction factor} = 1 - \frac{3}{4(n_1 + n_2 - 2) - 1}. \tag{3}$$

This method was chosen as it was recommended for ES calculation of controlled pre-test post-test design studies in meta-analyses based on simulation results showing its superior properties with respect to bias, precision, and robustness to heterogeneity of variance compared with other methods [20].

The corrected ES was then calculated as follows (Eq. 4):

$$\text{Corrected ES} = g \times \text{correction factor}. \tag{4}$$

The scale used for interpretation was specific to training research and based upon the one proposed by Cohen [21] to evaluate the relative magnitude of an ES. The magnitude of the ESs was considered negligible (<0.2), small (0.2–0.50), moderate (0.50–0.80), and large ($\geq$0.80). Finally, publication and small-study sample size biases were assessed using the extended Egger's test. Statistical analyses were carried out with STATA® version 12 (Stata Corporation, College Station, TX, USA).

4 Results

There was evidence of publication bias, as indicated by the Egger's test outcome ($p < 0.001$), which may simply be the byproduct of the large number of studies reporting an effect in the same direction (i.e., increase in performance after a CA) rather than genuine publication bias.

The PAP effect was small for jump (ES = 0.31), throw (ES = 0.28), and upper-body ballistic (ES = 0.23) performance activities and moderate for sprint (ES = 0.50) performance activity (Fig. 2).

With respect to the individual's characteristics (Table 1), stronger individuals exhibited a larger PAP effect (ES = 0.41) than their weaker counterparts (ES = 0.32). Moreover, individuals with a minimum of 2 years of resistance training experience expressed a larger PAP effect than those with less than 2 years of training experience (ES = 0.53 vs. 0.44), while inexperienced individuals exhibited considerably smaller ESs (ES = 0.07).

With respect to the various strength–power–potentiation complex components (Table 2), plyometric CAs (ES = 0.47) induced a slightly larger PAP effect than traditional high-intensity (ES = 0.41) and moderate-intensity (ES = 0.19) CAs, while maximal isometric stimuli resulted in a negative effect (ES = −0.09). Moreover, when a back squat was employed as traditional CA, a shallower depth

Fig. 2 Effect sizes for different performance activities. The values represent the mean and mean and standard deviation of the mean

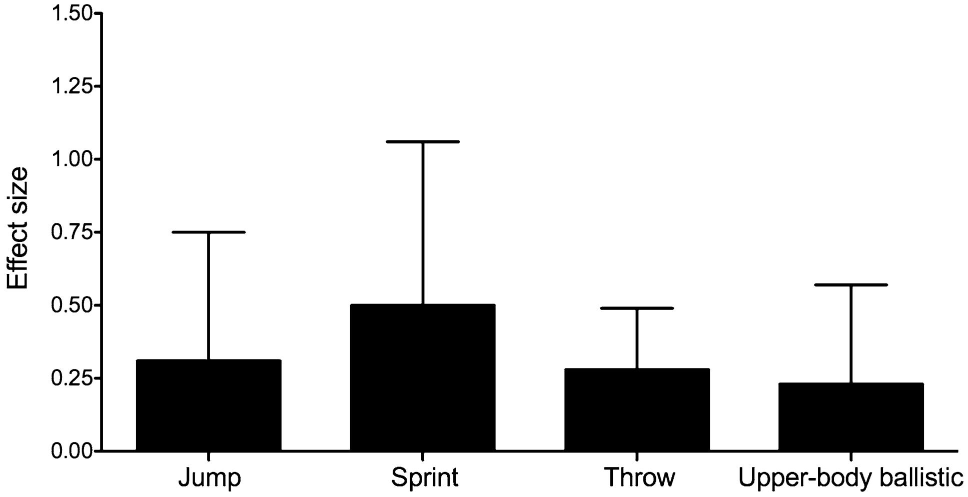

Table 1 Effect sizes for different subject characteristics

Independent variables	ES	SD	95 % CI	*n*
Strength level				
Stronger	0.41	0.33	0.31 to 0.51	43
Weaker	0.32	0.47	0.16 to 0.50	32
Resistance training experience				
>2 years	0.53	0.55	0.35 to 0.71	39
≤2 years	0.44	0.41	0.28 to 0.61	26
None	0.07	0.20	–0.08 to 0.23	9

CI confidence interval, *ES* effect size, *SD* standard deviation

Table 2 Effect sizes for different strength–power–potentiation complex components

Independent variables	ES	SD	95 % CI	*n*
Type of CA				
Traditional high intensity	0.41	0.46	0.29 to 0.52	66
Traditional moderate intensity	0.19	0.20	0.11 to 0.27	24
Plyometric	0.47	0.61	0.23 to 0.72	25
Maximal isometric	–0.09	0.19	–0.20 to 0.02	14
Squat depth of CA				
Parallel or below	0.25	0.33	0.15 to 0.34	48
Above parallel	0.58	0.49	0.34 to 0.82	19
Recovery post-CA				
0.3–4 min	0.17	0.32	0.10 to 0.25	67
5–7 min	0.49	0.47	0.33 to 0.64	38
≥8 min	0.44	0.60	0.22 to 0.66	30
Number of set(s) of CA				
Single set	0.24	0.32	0.17 to 0.30	103
Multiple sets	0.69	0.72	0.39 to 0.98	26
Type of load during the CA				
Repetition maximum	0.51	0.46	0.33 to 0.70	26
Sub-maximal	0.34	0.46	0.24 to 0.43	89

CA conditioning activity, *CI* confidence interval, *ES* effect size, *SD* standard deviation

produced a considerably larger effect (ES = 0.58) than a deeper depth (ES = 0.25). Longer recovery intervals between the CA and the subsequent performance activity produced a greater PAP effect (5–7 min, ES = 0.49; ≥8 min, ES = 0.44) than a shorter rest interval (0.3–4 min, ES = 0.17). Multiple sets of CA resulted in a considerably larger ES (ES = 0.69) than a single set (ES = 0.24), and using an RM load during the CA resulted in a larger effect (ES = 0.51) than using a sub-maximal load performed at a given percentage of 1 RM (ES = 0.34).

Table 3 shows the ESs for different strength–power–potentiation complex components for both stronger and weaker individuals. Traditional high-intensity CAs produced a larger PAP effect than moderate ones in both stronger (ES = 0.54 vs. 0.19) and weaker (ES = 0.34 vs. 0.30) individuals. Stronger individuals exhibited a slightly larger PAP effect after shallower (ES = 0.60) versus deeper (ES = 0.55) back squats, while their weaker counterparts experienced a considerably larger effect with a shallower depth (ES = 0.67) than with a deeper depth (ES = 0.12). Stronger individuals exhibited the greatest PAP effect 5–7 min after the CA, whereas their weaker counterparts achieved a delayed maximal PAP response, after at least 8 min of recovery. Moreover, while stronger individuals exhibited a larger PAP effect after a single set (ES = 0.44) of CA, weaker individuals exhibited a considerably greater PAP response following multiple sets (ES = 1.19). In addition, stronger individuals displayed a larger PAP response (ES = 0.60) when a RM load is used during the CA, while their weaker counterparts experienced a larger effect (ES = 0.35) with a sub-maximal load.

Table 3 Effect sizes for different strength–power–potentiation complex components for both stronger and weaker individuals

Independent variables	Stronger individuals				Weaker individuals			
	ES	SD	95 % CI	*n*	ES	SD	95 % CI	*n*
Type of CA[a]								
Traditional high intensity	0.54	0.35	0.40–0.68	26	0.34	0.53	0.12 to 0.57	24
Traditional moderate intensity	0.19	0.21	0.01–0.36	8	0.30	0.19	0.13 to 0.46	8
Squat depth of CA								
Parallel or below	0.55	0.34	0.37–0.72	16	0.12	0.25	0.00 to 0.25	18
Above parallel	0.60	0.33	0.18–1.01	5	0.67	0.58	0.23 to 1.12	9
Recovery time post-CA								
0.3–4 min	0.15	0.16	0.06–0.24	15	0.28	0.25	–0.12 to 0.67	4
5–7 min	0.62	0.30	0.49–0.75	23	0.31	0.70	–0.19 to 0.81	10
≥8 min	0.23	0.09	0.13–0.32	6	0.36	0.38	0.16 to 0.55	17
Number of set(s) of CA								
Single set	0.44	0.35	0.33–0.56	37	0.17	0.23	0.08 to 0.26	27
Multiple sets	0.21	0.10	0.08–0.34	5	1.19	0.51	0.56 to 1.82	5
Type of load during the CA								
Repetition maximum	0.60	0.42	0.32–0.88	11	0.28	0.35	0.03 to 0.53	10
Sub-maximal	0.36	0.28	0.25–0.46	30	0.35	0.52	0.12 to 0.58	22

CA conditioning activity, *CI* confidence interval, *ES* effect size, *SD* standard deviation

[a] Plyometric and maximal isometric variables not included because they were unavailable

5 Discussion

The purposes of this meta-analysis were to determine (1) the effect of performing a CA on subsequent jump, sprint, throw, and upper-body ballistic performances; (2) the influence of different types of CA, squat depths during the CA, rest intervals between the CA and subsequent performance, different volumes of CA, and different types of load during the CA on PAP; and (3) how individuals of different strength levels respond to these strength–power–potentiation complex components. The present data show that performing a CA improves subsequent jump, sprint, throw, and upper-body ballistic performances. Furthermore, in agreement with the hypotheses formulated, the level of potentiation is dependent on the characteristics of both the individuals and the strength–power–potentiation complex, and individuals of different strength levels respond differently to these various strength–power–potentiation complex components.

Close examination of the scientific literature reveals inconsistent findings regarding the PAP effect on jump, sprint, throw, and upper-body ballistic performance activities. For instance, Pearson and Hussain [22] reported decreases in jump height, jump power, rate of force development, and take-off velocity during countermovement jumps performed after different back squat CAs. Conversely, Kilduff et al. [23] observed increases in countermovement jump height and power output following a back squat CA. Regarding sprint performance, no changes in 5- and 10-m times were reported by Crewther et al. [8] after a set of back squats, whereas improved 40-yard dash performance was observed after completing a sled resistance sprint CA [24]. With respect to throwing performance, heavy medicine ball throws have been shown to decrease subsequent standing shotput performance [25], while increases in squat underhand front shot throws were observed after a drop jump CA [26]. Finally, Esformes et al. [27] reported decreases in ballistic bench press throw height and rate of force development after a concentric-only bench press, while power output was increased after a bench press CA in a study performed by Baker [10]. Therefore, at this time the precise effect of performing a CA on subsequent jump, sprint, throw, and upper-body ballistic performances remains unclear. The present meta-analysis, including 47 studies and 135 groups of participants for a total of 1954 participants, shows that the PAP effect is small for jump, throw, and upper-body ballistic performance activities and moderate for sprint performance activity. Based on the contemporary scientific literature and the current meta-analysis, it appears that PAP effects are relatively small, but the interpretation of this finding must be taken with care as it appears that PAP responses may vary between individuals.

Careful inspection of the scientific literature reveals that the PAP response is highly individualized and indicative of a responder versus non-responder phenomenon.

Specifically, the individual responsiveness to a CA may be partially explained by the fact that increases in performance after a CA are mediated by the net balance between fatigue and potentiation, which co-exist and predicate performance outcomes [4]. Therefore, performance may be enhanced if potentiation dominates fatigue, remain unchanged if fatigue and potentiation are at similar levels, or decrease if fatigue dominates potentiation. Ultimately, the relationship between fatigue and potentiation is thought to be influenced by the characteristics of both the individual and strength–power–potentiation complex [2]. Consistent with this assumption, the present meta-analysis indicates that the level of potentiation is dependent on the level of strength and resistance training experience of the individual, the type of CA, the depth of the squat when a back squat is used to elicit a PAP effect, the rest period between the CA and subsequent performance, as well as the number of set(s) and type of effort of the CA.

5.1 Influence of the Level of Strength and Resistance Training Experience on Post-Activation Potentiation (PAP)

The present meta-analysis suggests that stronger individuals are able to exhibit a greater PAP effect (ES = 0.41) than their weaker counterparts (ES = 0.32). This finding is in line with previous work [12–14] and may be explained by the fact that stronger individuals may have a greater percentage of type II muscle fibers [28, 29] and therefore a greater phosphorylation of myosin light chain [29, 30], which is one of the peripheral-level factors proposed as a mechanism underpinning PAP [31]. In addition, stronger individuals may develop fatigue resistance to heavier loads after a near-maximal effort [16, 17], which may affect the balance between fatigue and potentiation post-CA. Moreover, it appears that individuals with prior resistance training experience exhibit a considerably larger PAP effect (ES = 0.53 and 0.44) than those with no prior experience (ES = 0.07). This result makes sense from the perspective that inexperienced and less experienced individuals will likely exhibit lower strength levels than more experienced individuals and therefore lower levels of PAP.

5.2 Influence of the Type of Conditioning Activity (CA) on PAP

The present data suggest that plyometric (ES = 0.47) and traditional high-intensity (ES = 0.41) CAs produce considerably larger PAP effects than traditional moderate-intensity (ES = 0.19) and maximal isometric (ES = –0.09) CAs. Although the PAP phenomenon after traditional resistance exercise CAs such as the bench press and back squat has been extensively examined, there is limited research examining the effects of plyometric CAs on the occurrence of PAP. To the best of our knowledge, only one study directly compared the effect of a plyometric versus traditional resistance exercise CA and it reported a greater PAP effect after the former, although the difference did not reach statistical significance [32]. Therefore, the present meta-analysis provides the clearest evidence that a plyometric CA may be slightly more effective than a traditional resistance exercise CA to induce potentiation. One explanation for this finding is that plyometric exercises are associated with the preferential recruitment of type II motor units [33], which is one central level mechanism underpinning PAP [34]. Given the relationship between fatigue and PAP, a plyometric CA may produce less fatigue than a loaded traditional resistance exercise CA, allowing a greater potentiation effect to be achieved and reducing the time necessary to achieve the maximal PAP effect, although explicit testing of this hypothesis is warranted. Nevertheless, the present meta-analysis partially supports this hypothesis since a greater PAP effect can be realized earlier (i.e., 0.3–4 min) after the completion of a plyometric CA when compared with traditional high- and moderate-intensity CAs (i.e., $\geq$5 min).

Regarding traditional resistance exercise CAs, our data suggest that high-intensity CAs may be more effective than moderate-intensity CAs to induce potentiation, which contrasts with the findings of Wilson et al. [5] who found that intensities less than 84 % of 1 RM were more effective stimulators of performance. Nonetheless, our finding substantiates that of others who found that PAP is optimized following higher-intensity CAs [35, 36]. For example, Fukutani et al. [36] reported larger increases in jump performance after an ascending heavy-squat protocol up to 90 % of 1 RM than with a protocol performed at up to 75 % of 1 RM. Similarly, a bench press CA performed at 87 % of 1 RM was shown to be more effective than a 30 % 1 RM ballistic bench press effort to potentiate subsequent upper-body ballistic performance [35]. It is also important to note that the PAP effect is larger in both stronger and weaker individuals after traditional higher-intensity CAs than after lower-intensity stimuli. The superiority of higher-intensity CAs to induce larger PAP effects may partially be explained by the fact that they may increase the recruitment of higher-order (type II) motor units to a greater extent [37]. From the present data, it is not possible to determine how the individual's strength level dictates the PAP response following plyometric and maximal isometric CAs. Future research addressing this question is therefore required in order to develop a full picture of the influence of the type of CA on PAP.

5.3 Influence of the Depth of a Squat CA on PAP

When a back squat is employed as traditional CA, a shallower depth produces a considerably larger effect

(ES = 0.58) than a deeper depth (ES = 0.25), which contrasts with a recent study reporting a greater PAP effect after a parallel squat CA when compared to a quarter squat CA [6]. Our result may be explained by the fact that a full squat is likely to induce higher levels of acute fatigue than a partial squat because of its longer time under tension [7] and thus reduce the ability to express high levels of PAP.

It is worth noting that the effect of squat depth on subsequent performance is largely mediated by the strength status of the individual. Specifically, while shallower squats (ES = 0.60) produce a slightly greater PAP effect than deeper squats (ES = 0.55) in stronger individuals, they are far greater stimulators of PAP among weaker individuals (ES = 0.67 vs. 0.12). Although the large difference in ESs available must be taken into consideration when interpreting this result, it can be speculated that the longer time under tension of deeper squats may produce more fatigue than shallower squats [7] and thus limit the ability of the weakest individuals to express higher levels of potentiation. Conversely, stronger individuals who have a greater capacity to resist fatigue are likely to exhibit similar levels of fatigue following deeper and shallower squats and thus express similar levels of potentiation after both types of squat. From the present data it is not possible to determine whether shallower squats reduce the duration required to exhibit a PAP response. More research needs to be undertaken to determine the effects of different squat depths on the temporal profile of PAP.

5.4 Influence of the Rest Period Between the CA and Subsequent Performance on PAP

The present data show that the greatest PAP effect is realized after longer recovery intervals (5–7 min, ES = 0.49; ≥8 min, ES = 0.44) between the CA and the subsequent performance than after a shorter rest interval (0.3–4 min, ES = 0.17). This finding substantiates the data presented by Wilson et al. [5], who reported greater levels of potentiation after 3–7 and 7–10 min of recovery post-CA than with rest intervals that were shorter than 2 min. One explanation for this finding may originate from the work of Rassier and Macintosh [4], who proposed that fatigue and potentiation can coexist, and that performance increases if potentiation offsets the level of fatigue produced during the CA. Therefore, with shorter rest intervals, fatigue may dominate and reduce the ability to express PAP. Conversely, longer recovery intervals may result in a greater dissipation of fatigue, allowing PAP to become the dominant after effect post-CA. It is important to note, however, that the time necessary to realize the greatest PAP effect may be influenced by the type of CA. Specifically, the greatest PAP effect seems to be elicited 0.3–4 min after a plyometric CA and at least 5 min following traditional high- and moderate-intensity CAs. This finding is in line with a recent study demonstrating that the greatest PAP response is realized 1 min after the completion of a plyometric CA [38].

Additionally, the temporal profile of PAP appears to be dictated by the individual strength level: stronger individuals express their greatest PAP effect 5–7 min after the CA, whereas their weaker counterparts achieve their maximal PAP response after at least 8 min of recovery. This phenomenon has been evidenced by Seitz et al. [12], who found that stronger individuals expressed their greatest PAP response 6 min after a back squat CA, while their weaker counterparts required 9 min of rest [12]. The ability of stronger individuals to express their greatest PAP effect earlier may be explained by the fact that they develop fatigue resistance to heavier loads after a near-maximal effort [16, 17]. Given the relationship between strength, fatigue, and potentiation, stronger individuals may be able to dissipate fatigue quicker after the CA because of their greater capacity to resist fatigue and therefore may be able to achieve their maximal PAP response earlier than weaker individuals.

5.5 Influence of the Number of Set(s) of CA on PAP

Consistent with the observations of Wilson et al. [5], the present meta-analysis shows that multiple sets of CA (ES = 0.69) induce a considerably larger PAP effect than a single-set CA (ES = 0.24). Furthermore, it appears that the strength level of the individual mediates the PAP response stimulated by different volumes of CA. Specifically, while stronger individuals express greater potentiation levels after a single-set CA (ES = 0.44) than a multiple-set CA (ES = 0.21), weaker individuals seem to gain more benefit from CAs that require multiple sets (ES = 1.19). This finding may suggest that a single set of a CA may not be a sufficient stimulus to induce a potentiation effect in weaker individuals and that the increase in PAP from single to multiple sets outweighs the increase in fatigue in these individuals. The large difference in ESs available between single and multiple sets for both stronger (i.e., $n = 37$ vs. 5) and weaker (i.e., $n = 27$ vs. 5) individuals may have influenced this finding and must be taken into consideration. Theoretically, a multiple-set CA should produce more fatigue than a single-set CA and thus reduce the ability of weaker individuals to express high levels of PAP. Future research examining the influence of strength level on PAP after single versus multiple sets of a CA is therefore warranted. Furthermore, while volume appears to be one factor that impacts the expression of PAP responses, one must consider the impact of volume and intensity collectively when examining the ability to induce PAP responses.

5.6 Influence of the Type of Load Used During the CA on PAP

The present meta-analysis suggests that using an RM load during the CA produces greater (ES = 0.51) levels of potentiation than a sub-maximal load performed at a given percentage of 1 RM (ES = 0.34). Of note, it appears that the effect is mediated by the strength status of the individual. Specifically, the PAP effect is larger after an RM load among stronger individuals (ES = 0.60 vs. 0.36), whereas a sub-maximal load appears to be more effective among weaker individuals (ES = 0.35 vs. 0.28). Conceptually, fatigue may dominate after using an RM load during the CA in weaker individuals and therefore reduce their ability to realize high levels of potentiation, while a sub-maximal load may produce less fatigue and allow PAP to dominate, although this remains to be explicitly tested. Conversely, an RM load may allow PAP to dominate in stronger individuals because of their ability to resist fatigue after heavier loads and because such an effort may increase the recruitment of higher-order (type II) motor units [37] to a greater extent, resulting in a greater PAP effect.

6 Conclusion

The present meta-analysis shows that performing a CA produces small PAP effects for jump, throw, and upper-body ballistic performance activities, as well as moderating the effect for sprint performance. The data also suggest that the magnitude of potentiation is mediated by the strength level and resistance training experience of the individual, the type of CA, the depth reached during a squat when this exercise is employed to induce PAP, the rest period between the CA and subsequent performance, the number of set(s) of the CA, and the type of load used during the CA. Furthermore, from a practical standpoint, it is important to note that a greater PAP effect can be realized earlier (i.e., 0.3–4 min) after the completion of a plyometric CA than in traditional high- and moderate-intensity CAs (i.e., $\geq$5 min). This may be of interest for coaches seeking a more time-efficient way to incorporate PAP complexes in their training program. Moreover, stronger and weaker individuals appear to respond differently to the different components of a strength–power–potentiation complex. These are points worthy of consideration in order to design optimal strength–power–potentiation complexes. Nevertheless, the large difference in the number of ESs available and the fact that some papers were omitted from the analyses because they did not meet the inclusion criteria may account for some of the results and must be considered when interpreting these findings. In addition, it is worth noting that training studies supporting the use of PAP complex training are lacking and therefore it remains to be determined whether performing PAP complexes over time leads to greater training adaptations than interventions where the plyometric or speed exercises are not performed in a PAP format but rather in isolation.

Acknowledgments Both authors contributed to the conception and design of the study, and writing of the manuscript. Both authors contributed to the development of the search strategy analysis and to the acquisition of data. Laurent B. Seitz contributed to the analysis and interpretation of data. Both authors contributed to drafting the article or revising it critically. Both authors approved the final version to be submitted.

Compliance with Ethical Standards

Funding No sources of funding were used to assist in the preparation of this article.

Conflict of interest Laurent B. Seitz and G. Gregory Haff declare that they have no conflicts of interest relevant to the content of this work.

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