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Narrative Review

The effects of multiple factors on post-activation potentiation and performance enhancement: a narrative review

Eugenio Formiglio[a,†], Antonino Patti[b,†], Eneko Fernández-Peña[c,*], Valerio Giustino[b], Domenico Savio Salvatore Vicari[d,b], Alessandro Tamassia[a] and Marco Gervasi[a]
[a]Department of Biomolecular Sciences - Division of Exercise and Health Sciences, University of Urbino Carlo Bo, 61029 Urbino, Italy
[b]Sport and Exercise Sciences Research Unit, Department of Psychology, Educational Science and Human Movement, University of Palermo, 90144 Palermo, Italy
[c]Department of Physical Education and Sport, University of the Basque Country UPV/EHU, 01007 Vitoria-Gasteiz, Spain
[d]Department of Neurosciences, Biomedicine and Movement Sciences, University of Verona, 37124 Verona, Italy
[†] These authors contributed equally as first author

Purpose: The aim of this review was to examine the effects of various factors, including recovery time, conditioning activity, range of motion, gender, age, fiber type percentage, training experience, and supplement intake, on post-activation potentiation (PAP) and post-activation performance enhancement (PAPE). After clarifying the differences between these two potentiation strategies, the review examines the physiological mechanisms underlying these processes and their relationship with the aforementioned factors.
Methods: A literature search was conducted in multiple databases, using as keywords those factors, PAP and PAPE.
Results: PAP/PAPE appears to benefit athletes, adults, and individuals with a higher percentage of fast-twitch fibers more. To increase performance, it is recommended to use an intensity greater than 80% of one repetition maximum and high volumes. For trained subjects, a recovery time of 3 to 10 minutes is beneficial, while its effectiveness for untrained subjects is still unclear. Potentiation is greater when the primer exercise has a wide range of motion and is similar to the verification test. Additionally, supplementation with caffeine or creatine also contributes to the magnitude of potentiation. Finally, although there is evidence suggesting a net potentiation, the balance between fatigue and potentiation remains complex and unclear.
Conclusions: Each factor that interacts with PAP and PAPE should be evaluated individually to ensure the most appropriate conditioning activity for the athlete.

Keywords: fatigue, training, fast twitch fiber percentage, age, gender, supplements.

Introduction

The study of muscle contraction potentiation began in the 19th century [1]. Enhancement has traditionally been measured as a temporary increase in force in an isometric muscle contraction following a conditioning contraction [2]. There are three forms of activity-dependent potentiation: stair-step potentiation, post-tetanic potentiation (PTP), and post-activation potentiation (PAP) [3–6]. A known stimulus is applied before and after the conditioning contraction in all three cases to detect the potentiated response. Scaled potentiation, the oldest term, involves a progressive increase in the contractile response during repeated low-frequency stimulation [3,4]. PTP, which has been studied since the 1930s, consists of an increase in the amplitude of the contraction force after prolonged high-frequency tetanic stimulation [5,6]. The third form, PAP, is induced by voluntary muscle activation, whereas PTP is caused by involuntary tetanic stimulation [7,8]. The main difference between PTP and PAP is that the former increases the maximal force expressed during muscle contraction, while the latter promotes an increase in the peak power of muscle contraction [5–8].

In the 1980s, important investigations [9–11] pointed to possible increases in contractile activity in response to short maximal voluntary contractions (MVC). PAP induces peak contraction forces, diminishing the effect rapidly in the first 28 seconds and more slowly in the subsequent 8-10 minutes [10]. In 2016, the phosphorylatable light chain of the myosin molecule in type 2 muscle fibers was identified as a cause of PAP [12]. After the potentiation, the myosin light chain is phosphorylated, improving the sensitivity of the actin-myosin complex to calcium ions and increasing the rate of cross-bridge formation, resulting in a higher rate of force development (RFD) [6,13–15]. PAP is also more effective with low Ca^{2+} levels in the sarcoplasm [16]. Recently, the concept of "PAPE" (Post Activation Performance Enhancement) introduced by Cuenca-Fernández et al. aims to distinguish the non-localized performance enhancement resulting from voluntary conditioning activity (PAPE) from the localized potentiation resulting from electrically evoked conditioning activity (PAP) [1,17]. PAPE takes several minutes to become detectable and has a longer window of action than

PAP (at least several minutes). In addition, it can be largely explained by physiological responses, including increased muscle temperature, intracellular water accumulation, and other mechanisms [1]. Understanding of the phenomenon appears to be in its infancy, and the distinction between PAP and PAPE is an attempt to clarify the conceptual and physiological differences associated with these phenomena. The continuing confusion in the scientific literature regarding the terms "PAP" and "PAPE" must be emphasized.

In this regard, Boullosa et al. [18] propose a new taxonomy for the classification of strengthening in sports. This taxonomy includes the identification of the conditioning activity, the test, and the population of athletes. It is expressed in the following formula: Post-[CONDITIONING ACTIVITY] [VERIFICATION TEST] potentiation in [POPULATION] [18]. This proposal could avoid misidentifying physiological attributes, which should be studied separately while promoting the individualization and applicability of conditioning protocols in sports. In practice, the term PAPE is applicable in most cases in the literature, i.e., when a single exercise, performed as a test, follows a conditioning protocol. Otherwise, in order to distinguish the PAP phenomenon from PAPE, it is necessary to apply procedures to measure in physiological terms the mechanisms that determine the occurrence of one, or the other, or their possible coexistence. The current literature lacks uniformity, with many inconsistencies and a lack of precise definitions. This lack of clarity contributes to confusion among those trying to understand the subject. The confusion stems from the many similarities between the two phenomena, namely: (i) contractile force is enhanced, (ii) there is a certain delay before the enhancement is observed, which, speculatively, derives from 'fatigue' and (iii) the response is much greater in type II fibers (or in muscles with a large proportion of fast twitch fibers). However, other features point to substantial differences between the phenomena, namely, (i) the time course of their force increases differs, with an early effect (within seconds), as well as a delayed effect (after minutes), observed in PAPE; (ii) PAPE, but not PAP, may be strongly influenced by variations in muscle temperature and intramuscular fluid accumulation, and (iii) there is a possibility that neural mechanisms have an impact on PAPE, but not PAP. Furthermore, current research appears to support the differentiation of the two phenomena, showing that PAPE could be affected by PAP in the short time following a conditioning activity [1]. Since many scientific articles often do not consider the conceptual distinction between PAP and PAPE, in this review we will refer to the phenomena as they are expressed by the authors. Although this approach tends to unify the two concepts, the purpose of this review is not to clarify potential terminological errors in the reviewed articles, but to summarize which procedures and factors have a positive effect on performance.

Methods

Experimental approach to the problem

A literature search was carried out in September 2023. The following databases were searched: PubMed, SPORTdiscus, Scopus and Web of Science. Only peer-reviewed articles in English were selected. The following MeSH terms and keywords were used in combination with the Boolean operators AND and OR: "post-activation potentiation", "PAP", "post-activation potentiation", "potentiation post-activation", "post-activation potentiation enhancement", "PAPE", "performance", "strength performance", "strength training", "strength", "complex training", "force", "power", "myosin", "myosin phosphorylation", "neural" and "H-reflex". No additional filters or search restrictions were used. All articles found in this way were imported into a Mendeley database to find and remove duplicates.

Inclusion criteria

Studies were eligible for further analysis if they met the following inclusion criteria:

a) At least one of the acronyms, PAP or PAPE was present.
b) At least one of the acronyms, PAP or PAPE was combined with a protocol of pre-conditioning exercises and with assessments after a variable rest period (seconds to minutes).
c) Subjects could be of any gender or ethnicity.
d) There were no restrictions on the age of the subjects.
e) There were no restrictions on the strength levels of the subjects.
f) The conditioning activities could be performed with any equipment (standard barbell, trap bar, free body flywheel etc.).
g) The evaluation was performed before and after the conditioning exercise.
h) The conditioning exercises were inherent to exercises that could be prescribed with PRT (periodized resistance training).
i) The post-stimulus evaluation was carried out with jumping exercises (squat jump, long jump, CMJ, drop jump), sprinting (10, 20, 30 meters) and ballistic exercises (such as barbell throwing on a flat bench or weightlifting derivatives).
j) No limits were imposed on the level of experience of the subjects.

Results

Factors influencing the PAP phenomenon

The PAP phenomenon is strongly influenced by individual and exercise prescription and administration variables. The following are among the main factors influencing the manifestation of the PAP phenomenon currently found in the literature:

- Intensity of primer exercise and experience in weightlifting
- Recovery time
- Volume of the conditioning activity (sets and repetitions)
- Exercise used as a conditioning activity
- Joint range of motion during the exercise, e.g., depth in the squat
- Type of load of the conditioning activity (dynamic, isometric, isokinetic, power level, etc.)
- Gender and age of subjects
- Intensity of conditioning activity (% 1-RM)
- Substance ingestion (supplements for when translated)

Physiological mechanisms underlying PAP

We can single out two main physiological mechanisms responsible for the benefits associated with the use of PAP: myogenic factors, linked to conformational changes at the level of the muscle cell, and neurogenic factors, related to functional changes in the nervous system. The myogenic component involves the phosphorylation of the regulatory light chains of myosin (RLC) [19–25], whereas the neurogenic component involves an increase in the recruitment of higher-order motor units[19–21]. Several studies provide evidence of other musculoskeletal modifications that may contribute to the manifestation of the PAP and PAPE effect in both distance runners and healthy subjects, such as changes in pennation angle and muscle-tendon stiffness. However, further research is needed to confirm these findings [19,20,26–29].

Phosphorylation of myosin light chains

The phosphorylation of myosin light chains potentially enhances subsequent contractions by altering the structure of the myosin head through conformational changes [19,21]. Phosphorylation of RLCs makes the actin-myosin interaction more sensitive to Ca^{2+} in the myoplasm [30] especially at low Ca^{2+} concentrations, such as during tetanic or low-frequency contractions [13,31–33]. Animal studies have shown increased phosphorylation of RLCs and increased contraction tension in response to tetanic stimulation [22,23,34,35]. However, few studies have explored a similar response in human muscle. Stuart et al. [34] reported a significant increase in RLC phosphate in the vastus lateralis muscle ($P < .01$) and a significant enhancement of knee extensor tension after a 10-second isometric maximal voluntary contraction (MVIC; $P < .05$). A positive trend, although no significant correlation, was noted between the magnitude of the contraction enhancement and the amount of phosphate in the individual RLC units and between the enhancement and the percentage of type II muscle fibers ($P > .05$).

Variations in pennation angle

A study of the pennation angle of the vastus lateralis, measured by ultrasound, showed a significant drop 3-6 minutes after 3-second voluntary maximal contractions (16.2 ± 1.39 degrees precontraction vs. 14.4 ± 1.11 degrees after post contraction) [27]. Although this change accounts for less than 2 degrees, the authors suggest that muscle forces could be transmitted more directly to the tendon. However, it is unlikely that this change, observed as a late response (3-6 minutes) after the three-second MVCs, has affected the maximum PAP extension, which is normally observed after a few seconds [19].

H-reflex

Neurogenic factors involve an enhancement of central nervous system (CNS) efficacy through an enhancement of a monosynaptic reflex between the α motor neuron and the spinal cord [36–40].This reflex is called the Hoffmann reflex (H-reflex), and is mainly stimulated by electrostimulation and requires maximal muscle contraction to increase postsynaptic sensitivity to neurotransmitters. Tillin et al. [41] indicated that the α-motoneurons of fast fibers need a higher threshold potential than slow fibers. Maximal contractions pre-stimulate the fast fibers, facilitating subsequent lighter efforts with a reduced level of EPSP (excitatory postsynaptic potential). This could lead to the recruitment of more fibers. Research to fully understand the contribution of the neural component in improving performance through PAP is still ongoing. Folland et al. [40] investigated the importance of the H-reflex in muscular performance, using the Hmax/Mmax ratio obtained by EMG and assessing the maximum strength of the quadriceps femoris. The results show muscular improvements, but, according to the authors, reflex reinforcement (RP) did not produce any performance benefits. Xenofondos et al.[36] examined the effects of PAP by evaluating contraction torque and H-reflex amplitude after a 10-second maximal contraction. Again, no significant benefits were observed from increased neural excitability via the H-reflex. Bergmann et al. [42] explored the efficacy of jumps as conditioning to induce PAP. The research confirmed the lack of a significant contribution of the neural component in increasing performance. Thomas et al. [38] demonstrated how the use of transcranial magnetic stimulation and electrical femoral nerve stimulation led to improvements in muscle power expression after high-intensity exercise but no changes in measures of neural function. Finally, Zero and Rice [37] showed a depression of spinal and supraspinal responses following PAP, suggesting neural adaptation to maintain activation when muscle contraction is most reactive and to delay neuromuscular fatigue. In summary, the current research does not conclusively confirm the significant role of the neural component in increasing performance through PAP, but suggests that intramuscular mechanisms may be more relevant [36,38,40–42].

PAP and fatigue

The muscle's response to voluntary or electrically induced stimuli is influenced by its contractile history. Fatigue is the most obvious effect of the contractile history reflected by a muscle's inability to generate the expected level of force. However, fatigue can co-exist with post-activation potentiation (PAP) [29,36,43,44]. Any conditioning activity will fatigue the skeletal muscle, creating a coexistence between potentiation and fatigue responses. The net balance between the processes that cause fatigue and those that contribute to potentiation determines the overall impact on human performance [42]. The timelines of fatigue and PAP will determine the post-stimulus state, predominantly toward fatigue or potentiation [29]. The optimal recovery window depends on the magnitude and rate of decay of PAP and fatigue. Therefore, it is crucial to consider the effect of PAP-conditioning activities on fatigue. To summarize, peak PAP occurs immediately after the conditioning activity but does not necessarily coincide with peak performance due to simultaneous maximum fatigue. The relative magnitude of PAP and fatigue depends on the pre-conditioning activity and the characteristics of the subject being tested. Intense activities may generate greater PAP and fatigue, and vice versa. The time between the conditioning activity and the subsequent performance affects recovery from fatigue and, consequently, the effect of PAP. Determining the time window between the end of the conditioning activity and the start of PAP will require a series of trials and experiments. This aspect is crucial in the design of programs using PAP induction methods [43]. Immediately after a cycle of contractions, Gullich and Schmidtbleicher [45] and Gilbert et. al. [46] observed a decrease or absence of changes in RFD during isometric contractions (1 to 5 bench press MVCs from 90 to >100% of 1-RM with 3-5 min rest [45] and 5 back squats at 100% of 1-RM with 5 min rest between repetitions [46]). However, after 12 min recovery, isometric RFD started to increase showing a 13% significant increase at 20 minutes [46]. The same trend of no immediate change or decrease followed by a significant increase in peak power in the countermovement jump (CMJ) (7-8% after 8-12 min 1 set of squats at 3-RM) [47] and in the 30 m sprint performance (2-3% after 5 min of 10 back half squats at 90% of 1-RM) [48] has been also reported elsewhere. Overall, these results indicate that although studies of electrically stimulated contractions have shown maximum PAP immediately after an activation cycle [10], fatigue also is present in the early phase of those potentiation protocols involving voluntary, maximal contractions with the aim of improving performance (PAPE). Following a conditioning activity, fatigue dissipates at a faster rate than PAP, and at some point during the recovery period (which varies from subject to subject), an enhancement of subsequent explosive performance (PAPE) may be obtained [41]. When the volume of the conditioning activity is low, the effect of PAP is greater than fatigue, and an enhancement of subsequent explosive performance can be realized almost immediately. Indeed, as the volume of conditioning activity increases, fatigue becomes greater than potentiation, negatively affecting subsequent performance. Some evidence suggests that to benefit from the PAP phenomenon, a recovery period may not be necessary. Conversely, the performance of a subsequent voluntary activity may remain unchanged or decrease despite a recovery period. French et al. [49] for example, observed a significant increase in the drop jump (DJ) height and the peak twitch of isokinetic knee extension (+5.0% and +6.1%, respectively; $P < .05$) immediately after three 3-second sets of isometric MVC knee extensions, without any recovery period. Similarly, Gourgoulis et al. [50] reported a significant increase in CMJ height (+2.4%; $P < .05$) immediately after two back squats performed with 90% of a maximum repetition (1-RM). Chiu and co-workers [30] found no significant improvements in the peak power of three CMJs and three loaded squat jumps even after a recovery period of 5, 6, and 7 minutes, respectively, after five sets of a back squat with 90% of 1-RM. These CMJs, performed at different times after the conditioning activity, were performed with different loads (30%, 50%, and 70% of 1-RM, respectively), making it difficult to compare differences in performance over time. These results were supported by Mangus et al [51] who reported no change in CMJ height 3 minutes after a back-squat with 90% of 1-RM. Behm et al. [52] also observed no change in isometric peak force immediately after three 10-second MVCs. However, after a recovery period of 10-15 minutes, peak force had decreased (7-9%; $P < .05$). These contradictory results suggest that the PAP-fatigue relationship and its effects on subsequent voluntary activity are complex. The relationship between PAP and fatigue and the overall effect of contractile history on subsequent performance is influenced by various factors.

Level of strength, experience and individual characteristics

Khamoui et al. conducted a study [53] on 16 recreationally trained men to explore the effect of high-load back squat volume on several variables, including vertical jump height. Test sessions included control conditions without intervention and experimental conditions with back squats at 85% of 1-RM and varying volumes (sets of × repetitions) (1×2, 1×3, 1×4, 1×5). The effects over time were significant in terms of increased ground reaction forces and impulse but not for vertical jump height and take-off speed. In conclusion, the back squat at 85% of 1-RM, regardless of volume, did not enhance the vertical jump for recreationally trained men. The authors suggest that this approach may cause fatigue rather than strengthening and that a 5-minute rest may not be optimal to benefit from a strengthening exercise in this context. In a 2010 study by Berning et al.[54] involving 13 trained and 8 untrained men, the authors explored the effect of an isometric squat on the performance of a vertical jump with counter movement (CMVJ). The isometric squat involved overcoming the resistance offered by a barbell placed on the rack stops with a weight of 150% of each subject's 1-RM. Participants performed the CMVJ after two different warm-up conditions: one involved a 5-minute warm-up of low-intensity cycling, and the other involved 5 minutes plus a 3-second isometric squat with 150% of 1-RM. In the trained subjects, the addition of the isometric squat led to a significant increase in CMVJ at 4 minutes, and this increase was maintained even after 5 minutes. In the untrained group, no significant differences in CMVJ were found between the warm-up conditions. In summary, using an isometric squat in the warm-up can improve short-term power in strength-trained men, whereas it does not show the same effect in untrained men. Seitz et al. [55] divided 18 elite junior rugby players into strong and weak groups according to the ratio of their maximum repetition in the back squat to their body mass. After a conditioning activity (CA) consisting of 1 set of 3 back squats at 90% of 1-RM, each subject performed squat jumps at various intervals post-CA. Stronger individuals showed the greatest increase in strength between 3 and 12 minutes following the CA, whereas weaker individuals showed the greatest increase between 6 and 12 minutes. The strong group exhibited a significantly greater PAPE response in all post-AC tests. The most significant potentiation for the strong group was observed at 6 minutes post-AC, while for the weak group, it was at 9 minutes. The results suggest that stronger individuals may express PAPE earlier and with significantly greater responses than weaker individuals. However, the authors note that the effect of conditioning activity on the PAPE response could be influenced by non-isolated variables, suggesting that the use of a control group would have been more appropriate to assess the cumulative effects of similar protocols.

More recently, Harat et al. [56] examined the impact of isometric (ISO), dynamic (DYN), and control (CON) strengthening warm-up protocols on endurance performance on an ergometer in rowing. Forty collegiate rowers were divided into high- and low-experience groups. DYN significantly increased distance covered, average power, and anaerobic capacity for the more experienced rowers, while it did not significantly affect the less experienced ones. Mean power in DYN was higher than CON and ISO in all intervals between 15 and 75 seconds, suggesting that DYN may promote greater power over shorter distances, especially for experienced rowers. Finally, Guerra et al. [57] conducted a study on 24 male professional footballers tested for agility, muscle power, aerobic capacity, and body composition. Conditioning activities (CA) consisting of plyometric exercises and sled-pulling sprints were performed. In the first and second sessions, body composition, agility, power, and aerobic capacity were assessed. In the third session, CMVJs were performed 1, 3, and 5 minutes after the AC performance. Significant differences were found for CMVJ height 1, 3, and 5 minutes after the AC compared to baseline values (3, 58%, 5, 10%, and 48%, respectively). A significant positive correlation was found between general fitness level and PAP, including the increase in CMVJ height 5 minutes after the conditioning activity. When athletes were divided into groups according to their fitness levels, CA resulted in a significant rise in CMVJ height in both groups, but a significant difference was observed at each time point after PAP induction, with higher performances in fitter athletes. Finally, plyometric exercises combined with sled pulling sprints as CA improved CMVJ in fitter subject, highlighting the importance of fitness in the PAP response. Regarding subjective characteristics, Seitz et al.[12] examined the relationships between maximal voluntary post-activation potentiation (defined by the authors as PAP), maximal knee extension torque, transverse sectional area (CSA), quadriceps volume, and the percentage of myosin type II heavy chain isoform (MHC) in human skeletal muscle. Thirteen strength-trained men participated in the test protocol, which included isokinetic knee extensions before and after a conditioning activity. Significant correlations were found between maximum post-activation voluntary response, maximum knee extension torque, CSA, and quadriceps volume. However, the strongest correlation ($r = .77$) was with the percentage of MHC type II. The latter correlation was also significant after considering other variables, suggesting that the myosin type II isoform is critical for manifesting the PAP phenomenon in human skeletal muscle. In addition, in a 2018 study by Gervasi et al. [58] in which the percentage of fast twitch fibers in subjects who performed CMJ before and after a conditioning activity was determined, a strong relationship between higher percentages of fast twitch fibers and higher post-activation potentiation was found. Finally, Hamada et al. demonstrated that muscles with the shortest contraction times and the highest percentage of fast twitch fibers (type II) show the highest post-activation potentiation [59]. These results may suggest that subjects with fewer white fibers have a lower response or are non-responders to potentiation exercises. However, given the complexity of this phenomenon, there is considerable inter-individual variability in the PAPE response, and it should be evaluated individually.

Type of exercise used as a conditioning activity

Arias et al. [60] examined the efficacy of a strengthening protocol based on floor presses in generating the PAP effect and improving vertical jump height. Fifteen men participated in three sessions with intervals of at least 48 hours between sessions. Their maximum repetition in the deadlift (1-RM) was assessed on the first day. On the second, the participants performed one of two experimental sessions: a deadlift session or a control session. After a single maximal vertical jump, they performed five deadlift repetitions at 85% of the 1-RM (experimental group) or stood still for ten seconds (control group). The results showed that the height of the vertical jump in the 15 seconds following the take-off was significantly lower than in the control condition, suggesting that the take-off repetitions not only did not induce a PAP effect but reduced performance. Seitz et al. [61] examined the effects of strengthening from a single sled push on subsequent 20-meter sprint performance without resistance. After a familiarization session, 20 rugby players performed maximal 20-meter sprints without resistance. Subsequently, each player performed the same sprint exercise 15 seconds, 4, 8, and 12 minutes after a sled push loaded to 75% or 125% of their body mass. The results indicated that the sled push at 75% body mass improved sprint performance at 4, 8, and 12 minutes but slowed performance at 15 seconds. On the other hand, pushing with a sled at 125% body mass impaired sprint performance at all subsequent time points. Dello Iacono et al. [62] examined the effects of two barbell hip thrust (BHT)-based post-activation strengthening protocols on sprint performance. Initially, eighteen handball athletes performed maximal sprints of 15 meters. They then repeated the same sprints at 15 seconds, 4 minutes, and 8 minutes after two experimental protocols with BHT at 50% or 85% of 1-RM (50PAP and 85PAP). At 15 seconds, only the 85PAP significantly impaired sprint performance, showing greater decreases than the 50PAP. However, at 4 and 8 minutes, both protocols significantly improved performance at the 10th and 15th meters. When comparing the two protocols, the 85PAP resulted in greater improvements in the 10th meters after 4 and 8 minutes and in the 15 meters sprint after 4 minutes. Positive correlations were found between BHT 1-RM values and individual PAP responses. This study suggests that BHT exercises, whether moderate or intense, can induce a PAP response, but the effects depend on post-stimulus recovery and individual strength level. Beato et al. [63] evaluated the effects of a post-activation strengthening protocol through eccentric overload (EOL) and traditional weightlifting (TW) on the performance of a standing long jump (SLJ), countermovement jump (CMJ) and acceleration in ta 5-meter sprint. Ten male athletes performed 3 sets of 6 repetitions of half squat EOL or TW, followed by SLJ, CMJ, and 5-meter sprint tests at 1, 3, and 7 minutes in separate sessions in randomized order. Significant differences were found using both exercises for SLJ at 3 and 7 minutes and CMJ at 3 and 7 minutes. There were no significant differences between EOL and TW for the SLJ, CMJ, and 5-meter sprint. In conclusion, both exercises significantly improved performance of the SLJ and CMJ, but not the 5-meter sprint. Using both protocols, the optimal time window for achieving PAP is between 3 and 7 minutes. No differences were found between the EOL and TW exercises, indicating that both methods can be used to stimulate the PAP strengthening effect. Atalağ et al. [64] examined the effects of PAP through Back Squat (B-SQ) and Hip Thrust (HT) exercises on the performance of a vertical jump (VJ), 20-yard sprint and 40-yard run in physically active university students. Participants performed three experimental sessions: basal, with B-SQ, and with HT. Neither of the exercises, performed at approximately 90% of 1-RM, affected the performance of the VJ, 20-yard sprint, or 40-yard sprint with an 8-minute rest interval. Despite the absence of acute potentiating effects, the authors suggest that B-SQ and HT can be used interchangeably and safely during more extended training periods to avoid monotony. Downey et al. [65] confirmed the importance of the specificity of conditioning contractions for the manifestation of the PAP effect. The authors examined the impact of performance-specific or non-performance-specific isometric contractions on PAP. Strength-trained subjects performed 7-second isometric contractions using back squats, bench presses (as conditioning contractions), or a control condition (rest) before maximal vertical jump performance. While the back Squat improved the maximum vertical jump, surprisingly, the bench press reduced maximum vertical jump performance. These results suggest that conditioning contractions should involve muscles specific to the target performance movement. Finally, it is worth noting that the type of recovery performed between two high-intensity activities may also act as a conditioning activity. in fact, some authors have found that an active moderate-intensity recovery between two Wingate tests influences the performance of the second test with an increase in peak and average power. Such moderate-intensity activity between two high-intensity sessions could have a post-activation strengthening effect [66].

Range of Motion

Esformes et al. [67] in a study involving 27 semi-professional rugby players, compared the effect of PAP on parallel squat (PS) and quarter squat (QS) performance. After a CMJ, followed by a 10-min rest, participants performed three squats (parallel or quarter squat) at the maximum load of 3 repetitions in randomized order. After 5 minutes of rest, another jump with counter movement was performed. Both squats generated PAPs for jump height, peak power, impulse, and time of flight. However, the PS produced superior results compared to the QS. The greater the depth of the squat, the greater the increase in CMJ performance, with more gluteal activation and more work produced. Gago et al. 2017 [68] examined post-activation strengthening on plantar flexors by testing at different knee angles. Ten male athletes performed supra-maximal contractions of the plantar flexors before and after maximal isometric plantar flexion (MVIC) with the knee flexed and extended. The results showed that the configuration of the knee joint influences the measured parameters. After MVIC, the enhancement of the contraction torque and torque development rate was significantly greater at the extended knee. These results suggest that strengthening the gastrocnemius contributes in the short term to the overall improvement of plantar flexor contractions. Therefore, the knee angle should be considered when looking for an immediate strengthening effect on the plantar flexors. Krzysztof et al. [69] examined the responses (in terms of PAP) induced by bench press with different ranges of motion in subsequent bench press performances performed in ballistic form. Ten strength-trained males participated in four experimental sessions with different conditions and ranges of motion. The standard conditioning task of the bench press distension showed the greatest performance improvement in peak power and velocity under the conditions examined. The authors concluded that the range of motion of the conditioning task significantly impacts the magnitude of the PAP response, showing that a greater effect is obtained when the range of motion of the conditioning task and the subsequent explosive task are similar.

Recovery Time

Jo et al. [70] explored the effect of recovery time after an enhancing stimulus on muscle power in amateur athletes. During experimental sessions, subjects rested for 5, 10, 15, or 20 minutes after a back squat exercise before performing a Wingate Test. The results showed that although the control and experimental conditions did not differ significantly, absolute peak power, relative peak power, and fatigue index increased significantly compared to baseline values, regardless of the duration of rest. The duration of rest associated with the maximum PAP effect was significantly correlated with the relative 1-RM. In short, recovery duration did not influence post-exercise performance. By contrast, differences in individual strength may influence potentiation time, suggesting that stronger subjects may benefit from shorter rest periods (5-10 minutes), whereas weaker subjects may require longer periods (15-20 minutes). Gouvêa et al. [71] carried out 14 studies examining the effect of PAP through different rest durations on vertical jump performance, considering different recovery times. Rest intervals of 0-3 minutes were found to impair performance, while those of 8-12 minutes improved jump height. The manipulation of the rest interval influences the magnitude of the PAP. Do Carmo et al. [72] conducted a study on trained men, where self-selected rest interval (SSRI) and fixed rest interval (FRI) strategies were compared for PAP in countermovement jumping (CMJ) performance. The SSRI condition significantly improved CMJ height compared to FRI and control. SSRIs, with an average rest interval (of 5:57 minutes), were considered effective in inducing PAP in CMJ height in trained individuals. More recently, a meta-analysis was conducted by Chen et al. [73] on 9 studies with a total of 141 participants to evaluate the recovery time of PAP using squats as a conditioning activity. Squats with an intensity between 85% and 100% of the 1-RM significantly improved the 10- and 30-meter sprint performance with a time between 4 and 8 minutes. The analysis showed that the significance value was higher in athletes and ball games than in university students and games without a ball. Finally, Masel and Marcin [74] conducted a study in which 15 strength-trained men participated in an evaluation of the effects of a trap bar with accommodating resistance on squat jump (SJ) performance with different rest intervals (90, 120, 150 seconds). The 90-second experimental protocol significantly improved SJ performance, whereas the 120- and 150-second protocols yielded no significant improvement. In conclusion, a trap bar and accommodating resistance with a 90-second rest interval can significantly improve jumping performance, suggesting that exceeding the 120-s rest interval may not optimize the PAP effect.

The volume of the conditioning activity/contraction

A study conducted by Hamada et al. [24] explored the interaction between the volume of the conditioning activity (AC) and the effect of post-activation potentiation associated with fatigue. This effect was researched by performing 16 isometric knee extensions of 5 seconds each, with rest intervals of 3 seconds. The results showed a predominant PAP effect concerning fatigue in the first three isometric contractions, with a 127% increase in strength over baseline values ($P < .05$). By contrast, in the remainder of the protocol, the contraction torque decreased progressively, reaching a 32% decrease at the sixteenth extension ($P < .05$), showing an increase in fatigue as the number of MVCs increased. Later in the recovery period, the contraction torque gradually increased, exceeding the basal values after 30 and 120 seconds of recovery (+32%; $P < .05$), indicating that fatigue fades faster than PAP and triggering an enhancement of the contraction torque. Vandervoort et al. [10] recorded tension in the dorsal foot flexors before and after five MVC protocols of isometric foot dorsiflexion with different durations (volume), showing that a 10-second isometric MVC caused the greatest potentiation (+142%; $P < .05$). French et al. [49] examined the effects of different volumes of conditioning contractions (CC) on contraction torque during isokinetic knee extension, finding a significant increase after three 3-second isometric MVCs (+6.1%; $P < .05$), but a decrease after three 5-second isometric MVCs (3%; $P < .05$). In summary, the results of the three studies [10,24,49] show the influence of CC volume on the PAP-fatigue relationship. Despite the determination of a specific recovery period, it remains challenging to define the optimal CC volume due to the lack of standardization in methodologies. Naclerio et al. [75] examined the effect of three post-activation strengthening (PAP) protocols with different volumes and controlled intensity on the recovery time required to improve vertical jump performance in recreationally trained university athletes. Eleven participants performed countermovement jumps (CMJ) before and after three parallel squats at 80% of 1-RM: low volume (LV, one repetition), moderate volume (MV, three repetitions), and high volume (HV, three sets of three repetitions). CMJ heights were significantly lower at 3 and 5 minutes in the LV-HV ($P = .048$) and MV ($P = .005$) conditions. No significant differences were found within each volume protocol at the 15th second and all other time points tested. However, effect size analyses showed higher CMJ performance from 1 to 8 minutes for the MV and HV conditions compared to baseline and 15-second performance. In conclusion, no clear relationship emerged between the volume of the conditioning task and the optimal time for maximal performance in the subsequent explosive action. However, moderate and high-volume protocols were found to be more effective in eliciting potentiation than low-volume protocols, at least within 12 minutes. Similarly, Kilduff et al. [47] found a power output and jump height decrease 15 seconds after 3 sets of 3 back squats at 87% of 1-RM, but an increase in the same variables and the rate of force development at the 8th minute. Dello Iacono et al. [76] compared the effects of two PAP protocols using traditional set or cluster configurations on countermovement jump (CMJ) performance in basketball players. Participants performed loaded squat jumps (for maximum power output), following either a traditional or cluster set (with 20-second breaks every two repetitions). CMJ height measurements and kinetic variables were recorded before, 30 seconds, 4, and 8 minutes after the PAP protocols. In both conditions, subjects showed a decrease of 1.21 cm after 30 seconds, an increase of 2.21 cm after 4 minutes, and 2.60 cm increase after 8 minutes compared to the start. However, the cluster condition produced higher jumps of .71 cm, 1.33 cm, and 1.64 cm at 30 seconds, 4, and 8 minutes, respectively. Both protocols induced PAP responses, but the cluster configuration induced superior jump performance by better utilizing the PAP effect and improving mechanical responses, reducing fatigue. The authors suggest that the cluster approach is an effective and practical method to improve vertical jump performance with a negligible time cost.

Static, dynamic, or plyometric contraction and potentiation

The effectiveness of the PAP effect may depend on the type of contraction. However, the literature contains mixed results and studies have mainly focused on isometric or dynamic voluntary contractions, making it difficult to establish a clear relationship between the type of contraction and the PAP response. Rixon et al. [77] directly compared strengthening from isometric and dynamic back-squats and found a greater increase in jump height and peak power after isometric contractions. However, the two conditions differed in volume and frequency, complicating the comparison between them. Other studies [78,79] have shown that dynamic and isometric contractions generate neuromuscular fatigue in distinct ways, with isometrics inducing greater central fatigue. Indeed, dynamic contractions intermittently promote blood flow, reducing metabolite accumulation and peripheral fatigue compared to isometric contractions. Isometric conditioning activities may cause greater central fatigue but activate peripheral PAP mechanisms, whereas dynamic activities may cause greater peripheral fatigue but activate central PAP mechanisms. The interaction between these mechanisms and their effects on subsequent explosive activities requires further investigation [77–84]. Esformes et al. [85] examined the effects of PAP through isometric, concentric, eccentric, and concentric-eccentric contractions on upper-body strength and power performance. Ten male rugby players performed a ballistic bench press stretch pull (BBPT), followed by one of the conditioning contraction protocols, on separate days and in a randomized, counterbalanced order. After a 12-minute rest, they performed another BBPT. The isometric contractions showed a significant increase in peak power, while no significant differences were found in the other conditions. The research suggests that isometric contractions could benefit in situations of prolonged inactivity, such as during competitions or training, if followed by an adequate rest period. Maloney et al. [86] examined the differences between pre-activation protocols to induce PAP using heavy resistance exercises and low-load plyometric or ballistic exercises. The ability to achieve PAP without heavy equipment makes plyometric or ballistic exercises more practical prior to competitions. Low-load ballistic exercises can induce PAP due to the high recruitment of type II muscle fibers, with increases in power performance generally ranging between 2% and 5%. Jumps with additional loads, such as depth jumps or weighted jumps, are considered the most effective activities for inducing PAP. The optimal recovery duration requires further research, but recoveries of 1-6 minutes have been shown to be effective in several cases. Turner et al. [87] studied the impact of plyometric training on sprint acceleration performance in trained men. Specifically, the study aimed to investigate whether plyometric exercise, performed with and without a weighted vest, enhances sprint acceleration performance over 10 m and 20 m and whether the magnitude of the improvement in individuals' performance was related to their baseline performance. Therefore, participants completed three experimental trials after a standardized warm-up and a basal 20meter sprint assessment. Immediately after the sprint, in an order determined by block randomization, participants were subjected to one of the following protocols: a control walking condition (C); a preload stimulus of 3 sets of 10 plyometric bounds with only the resistance of their body mass (plyometric condition, PLY); a stimulus of 10 plyometric bounds with an additional load of 10% of their body mass (weighted plyometric condition, WP). The sprints were retested after 15 s and after 2, 4, 8, 12, and 16 minutes compared to the end of the three experimental conditions; at 15 s, the protocol with 10% body mass overload reduced the speed over 20 meters compared to C, but at 4 and 8 minutes showed significant improvements over both distances. The PLY condition also showed improvements at 4 minutes over 10 meters. Overall, plyometric training proved to be an effective strategy to enhance acceleration performance in sprinting, with the PAP effect enhanced by using overload. The authors emphasize the practical importance of this activation in improving athletes' pre-race preparations. Hughes et al. [88] examined the effectiveness of an accentuated eccentric load compared to a traditional back squat to improve jumping performance. Eleven men performed 3 CMJs before and 6 minutes after each PAP protocol. The analysis revealed a significant jump height enhancement with the accentuated eccentric load, whereas the BSq showed no significant difference. These results indicate that jump performance may benefit more from the eccentric muscle action than the traditional back squat protocol. From a practical standpoint, an accentuated eccentric load could be more logistically convenient to integrate into pre-competition warm-ups, offering a similar or even greater PAP effect in a shorter recovery period (1-6 minutes). This could facilitate the implementation of such a protocol as part of pre-competition athletic preparation. Ulrich and Parstorfer [89] compared the effects of plyometric (PLY), concentric-eccentric (CON), and eccentric-only (ECC) conditioning activities on upper-body power performance via the PAP effect. Sixteen men trained in strength training performed experimental tests in randomized order. Power in the bench press was measured before and after each conditioning activity. PLY and CON significantly increased performance compared to individual baseline performance. ECC did not yield improvements. In conclusion, the PLY conditioning activities generated a 5% increase in upper-body performance by generating a PAPE effect. Recovery times of 8-12 minutes maximize power gains, making PLY conditioning activities attractive in pre-competition warm-ups to improve upper-body performance. Beato et al. [90] evaluated the effects of post-activation strengthening through eccentric overload (EOL) exercises on countermovement jumping (CMJ) performance and isokinetic muscle strength in the lower limbs. Eighteen active men performed 3 sets of 6 repetitions of EOL half squats compared to a control condition (cycling for 10 minutes). The EOL group showed significant differences in CMJ height from 3 minutes post-exercise, peak power from 1 to 9 minutes, and isokinetic strength of the quadriceps and posterior thigh muscles from 3 to 9 minutes post-exercise. In conclusion, using an EOL protocol improved height, power, and strength during CMJ, suggesting an optimal time window for PAPE between 3- and 9-minutes post-exercise. Timon et al. [91] examined the effect of a squat exercise protocol with an inertial flywheel on jumping performance. Sixteen participants completed two protocols: one traditional and one with the inertial flywheel. Both consisted of 3 sets of 6 repetitions with the power maximizing load and 3 minutes rest between sets. Squat jump height, speed, and power were measured before and at 4, 8, and 12 minutes after the stimulus. The inertial flywheel protocol showed significant height, speed, and power increases compared to the traditional protocol, especially at 4 and 8 minutes after the exercise. In conclusion, the inertial flywheel protocol enhanced SJ between the 4th and 8th minute, suggesting that this pre-conditioning strategy could be useful in pre-competitive warm-ups, especially for explosive activities. The review conducted by Beato et al. [92] analyses PAP protocols using eccentric flywheel overload (EOL) exercises. Seven studies were analyzed, yielding some interesting conclusions. First, different inertia intensities can be used to improve sport-specific performance depending on the selected exercise. Secondly, the PAP time window following the EOL exercise follows the principles of the traditional PAP literature, with acute fatigue emerging in the first part of the recovery (e.g., 30 s) and the benefits of the PAP effect occurring in the second part (e.g., 3 and 6 minutes). In addition, a volume of 3 sets and 3-8 repetitions with longer recoveries as the number of repetitions for the conditioning activity increases is a sensible approach to reduce transient muscle fatigue and maximize the potentiating effect. Athletes should gain experience with EOL exercises before integrating them into a PAP protocol. Finally, the size of common flywheel devices offers practical solutions to induce PAP effects outside traditional training environments. The authors suggest that EOL exercise may be an alternative method to achieve performance benefits in various sports. Still, future research is needed to optimize intensity, volume, and rest intervals to maximize the PAP phenomenon and have greater benefits in athletic performance. Finally, Brink et al. [93] reported the results of a systematic review and meta-analysis that examined whether a conditioning activity using body weight as a load can improve performance through the after-activation effect. Nineteen randomized controlled trials with healthy adult subjects were included in the review. In these studies, the conditioning activity using one's body weight was compared to a control condition in which the PAP intervention was excluded. The results indicate that a conditioning activity using body weight before performing a maximal vertical jump or sprint can induce a PAP response, offering a small performance advantage.

Gender and age of subjects

Arabatzi et al. [94] examined the effects of post-activation strengthening on the squat jump (SJ) and peak force development (RFD peak) in preadolescents, adolescents, and adults of both sexes. Participants performed SJs before and after an isometric conditioning stimulus. The RFD peak increased with increasing age in both males and females. An improvement in performance in the SJ was only observed in males after the conditioning stimulus, whereas no significant effect was found in females and young people. The authors conclude that the PAP effect on SJ height is sex- and age-dependent, with a benefit observed only in adult men. An isometric conditioning activity as a conditioning stimulus is effective for acutely improving SJ vertical performance in men but not in the pediatric/adolescent population. Ishak et al. [95] explored gender differences in post-activation potentiation (PAP) responses in team sports athletes, focusing on the optimal duration of post-stimulus recovery. After a standard warm-up, 24 participants (12 males and 12 females) performed a series of 5 back-squats repetitions, each at 85% of each participant's maximum. (16). After the stimulus, participants rested passively for a total duration of 4 minutes, 8 minutes, or 12 minutes. After recovery, they were instructed to sequentially perform a countermovement jump (CMJ), a 20-meter linear sprint, and a t-test for agility assessment. Subsequently, physical performance was assessed. The results indicated that all performance measures were significantly better at 12 versus 4 and 8 minutes for both males (1.50% increase to 2.95%) and females (1.09% increase to 5.79%) ($P < .05$). In addition, the 12-minute condition showed significantly lower values of heart rate (3.18 to 5.15 beats/min; $P < .005$) and perceived exertion (RPE) (.63 to 1.02; $P < .05$) compared to 8 and 4 minutes. Males performed better in all tests (increase from 19.33% to 26.34%) than females ($P < .005$). The authors conclude that a preload stimulus consisting of 5 repetitions of back squat at 85% of 1-RM can generate a PAP response. In particular, a 12-minute passive rest after the preload stimulus improved physical performance measures in both male and female team sports athletes [94]. Dello Iacono et al. [96] examined the effects of PAP protocols on young, trained athletes, focusing on 26 adolescent handball and basketball players. The aim was to evaluate whether two jumping protocols (drop jump and alternating leg drop jump) could improve explosive performance in young male athletes. Performance was assessed by countermovement jumping (CMJ) and 20-meter sprints. Both PAP protocols significantly reduced vertical jump and sprint performance compared to baseline. The authors concluded that PAP protocols with single-leg or two-leg drop-jump are associated with reduced performance in subsequent vertical jumps and linear sprints in young team sports athletes. Therefore, they recommend avoiding using such stimuli before these exercises in adolescent boys, suggesting that coaches should consider the level of motor experience and competence before introducing drop-jump exercises into the training or warm-up program. Titton and Emerson [97] conducted a study on elite young footballers (age 16.3 ± .6 years old), examining the acute effects of different protocols to induce post-activation strengthening. Using the squat exercise at four different intensities (40%, 60%, 80%, and 100% of a maximum repetition, 1RM), they evaluated the effects on the CMJ at four different recovery times (1, 3, 5, and 10 minutes). Twenty-five young football players participated, and five experimental sessions were performed. The different squat intensities did not show significant increases in CMJ height. However, significant differences in performance emerged concerning the various proposed recovery times. The 1-minute interval was the best option compared to 3 minutes ($P < .05$), 5 minutes, and 10 minutes ($P < .001$) for the maximum CMJ height. In average jump performance, the 1-minute interval produced superior results ($P < .001$) compared to the other intervals. The 10-minute recovery resulted in poorer performance than all the other intervals ($P < .001$). In summary, the results indicate that, regardless of the intensity of the squat exercise, the 1-minute recovery time appears to be more appropriate for promoting an increase in vertical jump in elite young footballers. However, it is important to note that these data are not sufficient to prove the presence of true enhancement.

Intensity of the conditioning activity/contraction

When using strength training exercises as a conditioning activity (AC) to promote post-activation strengthening, high loads are usually recommended to promote the involvement of the higher threshold motor units in type 2 muscle fibers. However, performing similar movements with moderate loads in an explosive manner can equally activate these high-threshold motor units. Moderate load strength exercises are an advantageous alternative, especially for weaker individuals, as they can reduce fatigue [98]. Fukutani et al. conducted a study on Olympic lifters in 2014 [99] examining the influence of squat exercise intensity on subsequent jump performance and PAP manifestation. Six national-level athletes with a squat-to-bodyweight ratio of 2 participated in the experiment. The conditioning protocols, named 'heavy condition' (HC) and 'moderate condition' (MC), varied in intensity (%1RM). Before and after squats, participants performed CMJ and were monitored by electromyography. The authors showed that contraction force and jump height increased significantly after squats, with a higher increase in HC than in MC in both conditions. The researchers concluded that high-intensity squats are more effective than moderate-intensity squats in improving subsequent jump performance. Bauer et al. [100] examined the effect of PAP related to the degree of intensity of squat exercise on subsequent jumping performance as assessed by countermovement jumping (CMJ). Sixty men with weightlifting experience participated in the study and were divided into three groups: high intensity (HI), moderate intensity (MI), and control group (CTRL). After familiarization, the subjects performed a PAP protocol with three sets of back squats at MI (60% 1-RM) or HI (90% 1-RM) and a control group (20-second rest), alternating with 7 CMJs assessed at different time intervals (15 seconds and 1, 3, 5, 7, 9 and 11 minutes after the back squat or rest). CMJ performance decreased immediately after squats but increased between 3 and 7 minutes after recovery for both intensities. The researchers concluded that back squats at MI and HI can enhance

CMJs through a contrast training protocol, but a recovery of at least 3 minutes after squats is required to benefit from the PAPE effect. Skurvydas et al. [98] conducted a study to explore PAPE and other parameters, such as low-frequency fatigue (LFF), metabolism-induced fatigue, and post-contractile depression (PCD), in response to different isometric muscle contraction modes. One hundred twenty healthy men, randomly assigned to ten groups, participated. These groups differed in contraction duration, activation pattern, activation mode, and intensity. Assessments were made by measuring maximum voluntary isometric contractions (MVCs) and knee extension torque after exercise. Muscle contraction modes with a short duration of maximal contraction (5 seconds) proved the most effective in achieving the PAP. In comparison, those with 12 contractions of 5 seconds showed the lowest effectiveness of PAP. Furthermore, exercise protocols involving short repetitive contractions showed a significant increase in contraction velocity compared to those involving more prolonged continuous contractions. Tetanic maximal torque enhancement occurred primarily after exercise modes that involved repetitive contractions of short duration or electrical stimuli. The researchers conclude that PAP is most effective after exercises with short, repetitive contractions. Paolo et al. [101] examined the effect of PAP on CMJ in 16 national-level swimmers using four conditioning activity (AC) protocols in different set and load configurations. The first AC included a set of five repetitions at 100%, while the other always included five repetitions, but this time at 65% of the 5 RM load (TS65). The other two ACs included a series of five repetitions with 30-second intraset rests between repetitions with the same relative loads. The researchers concluded that the traditional configuration of a continuous series with 5-RM significantly improved CMJ performance, suggesting that this approach can improve performance in highly trained athletes. Krzysztof et al. [102] examined the AC effect on bench press throw (BPT) performance in strength-trained men. After a data analysis of a sample of 174 subjects, the results showed a small PAP effect in the BPT (ES = .33). A single AC series at moderate intensity (60-84% 1-RM), performed 5-7 minutes before the explosive activity, produced a slightly higher improvement than multiple series or intensities above 85% 1-RM. Moderate rest intervals showed a more pronounced PAP effect than shorter or longer intervals, depending on the AC intensity.

Supplementation

Wang et al. [103] examined the effects of creatine supplementation on athletes practicing explosive disciplines during complex lower-body training. Thirty participants were divided into groups receiving either a creatine supplementation or a placebo. After six days of supplementation, the group taking creatine showed a significant increase in 1-RM strength and a decrease in individual PAP time compared to the placebo group. No significant differences in explosive performance were observed. In summary, creatine supplementation improves maximal strength and optimal PAP time but does not affect explosive performance. In a subsequent study [104] the same authors examined the effects of creatine supplementation on muscle strength, power, and PAP time in the upper body of canoeists. As in the previous study, there was a significant increase in maximum strength and a significantly shorter time to PAP effect in the experimental group taking creatine compared to the placebo group. However, there were no significant changes in power. Guerra et al. [105] examined the effects of PAP with and without caffeine intake on CMJ performance. Participants performed plyometric exercises and sled pulling for 60 min after taking a placebo or caffeine (5 mg/kg). The PAP protocol consisted of simple jumps, hurdles, and sled sprints. The CMJ was assessed before and 1, 3, and 5 minutes after the conditioning stimulus. Results showed a significant increase in jump height after the PAP protocol, with caffeine generating a higher response than the placebo. Jump height showed significant improvements in all conditions with caffeine (1, 3, and 5 minutes after the stimulus), whereas with the placebo, it only showed improvements at 3 minutes after the stimulus. Filip-Stachnik et al. [106] evaluated the acute effects of caffeine ingestion and back squat conditioning activity on countermovement jumping (CMJ) performance. The study involved three different test conditions in randomized order: 6 mg/kg caffeine (CAF), placebo (PLAC), or control condition (CTRL). Subjects performed a single set of back squats at 80% 1-RM (with repetitions performed until mean movement velocity dropped by 10%) as the conditioning activity or no activity in the control condition. Jump heights were assessed before and up to 10 minutes after the conditioning activity. No significant differences in jump heights were found between the CTRL and CAF conditions, but a significant decrease was observed in the eighth minute in the CTRL condition. The CAF condition showed a significant increase in the second minute, with no difference from baseline values in the PLAC condition. Furthermore, both the CAF and PLAC conditions showed a significant increase in jump height compared to the baseline in the post-conditioning values. In conclusion, a single set of back squats with heavy loading and controlled speed improved the CMJ's subsequent performance, whereas evening caffeine intake did not influence performance or increase the PAPE effect. Oliveira et al. [107] conducted a study on PAP and carbohydrate oral rinse (CHO). The experimental hypothesis evaluated the effect of their combination on repeated sprint ability (RSA). The experimental conditions included a placebo, an oral rinse with CHO, PAP with a placebo, and PAP with CHO. The PAP protocol consisted of two sets of 5 repetitions of back squats at 80% 1-RM. The results showed that PAP + CHO and PAP + placebo significantly improved sprint performance compared to the placebo and oral rinse with CHO. PAP positively influenced RSA performance in football players, but the combination of PAP and oral rinse with CHO did not affect performance.

Less explored methods of inducing PAP

A variety of PAP application methodologies were found to enhance performance. Any type of muscle contraction can be effective (only eccentric, isometric, dynamic, and only concentric) and the use of additional training equipment such as flywheel devices.

This paragraph has been written only to make readers aware that other methods have also been used to obtain PAP and a possible PAPE.

Accommodating resistance training

Training with the addition of chains or elastic bands has been shown to be a method for rigorously increasing the power levels of athletes if the proper precautions are taken in the weight room. One such precaution is that the elastic should offer resistance and, therefore, be in maximum tension at the start of the movement and that it loses the resistance it offers at the sticking point. Currently, studies can be found in the literature demonstrating the effectiveness of this methodology for the manifestation of PAP, showing that through the use of accommodating resistance, the phenomenon can be manifested with recovery times between the conditioning activity and the subsequent explosive activity [108–110]. Mina et al. [109] compared the effects of using squats with or without elastic bands on vertical jump performance. Fifteen men performed maximal CMJs after a specific warm-up and three repetitions of squats at 85% 1-RM with (VR) or without variable resistance (FWR), with 35% of the weight offered by the elastic bands in the VR group. Subsequently, three CMJs were performed at 30 seconds, 4 minutes, 8 minutes, and 12 minutes after the conditioning activity. The results show that using variable resistance led to significant improvements in CMJ performance, whereas there were no significant changes with squats without variable resistance. Significant increases ($P < .05$) in CMJ height (5.3% -6.5%), maximum power (4.4% -5.9%), force development velocity (12.9% -19.1%), concentric knee angular velocity (3.1% -4.1%) and mean concentric vastus lateralis activity (27.5% -33.4%) were found at all time points following VR. The study described above was confirmed in a systematic review and meta-analysis conducted by Huerta Ojeda et al. [110] which examined the effects of VR on muscle power in sports requiring explosive performance. Studies published between 2012 and 2022 were analyzed, assessing methodological quality and risk of bias. The results showed that using VR significantly increased jump height and time reduction in various sprint tests but had a negligible impact on throwing speed. Overall, VR has been shown to be effective in activating performance enhancement through PAP in multiple forms of exercise. Seitz et al. [108] examined whether a four-series box squats protocol could induce a PAP effect with additional resistance provided by elastic bands at 85% of 1-RM. In this study, fourteen rugby players performed four box squats (with a band load at 85% 1-RM) alternated by four broad squat jumps with a 90-second rest between the series. The control group elicited only the four maximal Brad jumps. After four box squats (85% 1-RM), the distance in the standing long jump improved to 5.7 ± 4.7%, especially after the first series. In addition, the manifestation of PAP was greater in stronger athletes. The results suggest that the PAP effect can be achieved with a contrast protocol accommodating resistance.

Acupuncture

Acupuncture is a traditional therapeutic practice in Chinese medicine that involves the insertion of thin needles into specific points of the body. It is believed that acupuncture can influence the body's energy flow, called 'Qi,' to restore balance and promote general well-being. Although its exact mechanisms are still being studied and debated, acupuncture has been used to treat a wide range of conditions, including chronic pain, stress, anxiety, insomnia, nausea, and other ailments. In addition to being used by many athletes, this methodology has recently been the subject of several research studies, which have evaluated its effectiveness in positively influencing PAP on shoulder muscles [111–113]. In the study by Wang et al. [111], twenty healthy female volunteers were given a 15-minute acupuncture protocol in the area around the shoulder before and after a battery of strength tests. The authors found significant increases after acupuncture in the average maximum torque in flexion, extension, and adduction; the average work, the average power, and the total work in flexion/extension and adduction/abduction; the total net sagittal-plane work (flexion + extension); and the total net frontal-plane work (adduction + abduction). However, although the results support the hypothesis that acupuncture can increase muscle excitability with a PAP effect, it must be emphasized that the study was not blinded, and therefore, a placebo effect cannot be ruled out. Wang et al. [112] explored the effect of acupuncture on the explosive force generated by the shoulder joint in young male subjects, finding that after acupuncture, isokinetic muscle parameters such as maximum torque, mean power, mean peak power, mean work and total work in adduction and abduction were significantly increased ($P < .05$).These improvements gradually decreased and disappeared approximately 10 minutes after treatment. This study did not include a sham acupuncture intervention, so a placebo effect could not be ruled out. Finally, Wang et al. [113] evaluated the effects of traditional acupuncture (TA) versus sham acupuncture (SA) on explosive force production and stiffness of the male knee joint. SA is an acupuncture method that involves the use of blunt-tipped needles pushed against the skin, giving the illusion of insertion. This study also demonstrated an increase in explosive force and a time-dependent increase in maximum torque, mean work, mean peak power, and total work, but only for the TA group ($P < .05$), inducing PAP. SA therapy did not produce significant increases ($P < .05$).

Blood flow restriction (BFR)

BFR is one of many training prescription methods for increasing strength, power, and mass. BFR has been shown to achieve gains equal to or similar to exercises with high loads. The main difference between BFR and classic weight training exercises is that similar gains do not require high loads, but the same exercise can be performed with partial vessel occlusion applied close to the origin of the target muscle and a lower percentage load. This allows trainers and athletes to achieve similar gains to those obtained in the weight room but with easily transportable loads directly on the training or competition field [114–117]. In a 2004 study by Moore et al. [118], after 8 weeks of elbow flexion training with (OCC) and without (CONTROL) vascular occlusion, the effects of PAP were compared both at baseline and after the training period. Compared with the baseline, the degree of PAP evident in torque was similar between arms and increased by 52% after training only in the OCC condition; however, the absolute PAP of torque was similar to that of control both before and after training. Zheng et al. [115] investigated whether different vascular occlusion conditions may or may not improve vertical jump performance. Various degrees of BFR combined with several levels of load intensity produced different gains, showing how low to moderate degrees of BFR interventions yielded similar PAPE results to traditional activation and these PAPE results were longer lasting than those of the control group. A systematic review conducted by Tian et al. [116] also confirmed the studies described above noting that the strategy of using BFRs during a conditioning activity rather than traditional methods may be more efficient and practical for inexperienced subjects and athletes not belonging to disciplines where power plays a key role.

Discussion

In this review, the main aspects of the PAP/PAPE phenomena were addressed through an in-depth analysis of scientific articles, which are summarized in Table 1. The studies analyzing the factors underlying the phenomena bring to light the distinction between PAPE and PAP, whereby the former seems to be mainly linked to increased temperature, the accumulation of intracellular water, and the existence of neural mechanisms that have yet to be clarified [1]. In contrast, increasing myosin light chain phosphorylation is associated with the PAP phenomenon [1,7,24,25,29,30,32]. Furthermore, there is some evidence that PAP has a significant effect on PAPE, especially in cases where many physiological processes have already been activated during a thorough muscle warm-up. However, PAPE may only be affected by PAP shortly after a conditioning activity, as it is rarely observed when PAP is at its maximum [1].. While this corroborates the notion of differentiation of the two phenomena, it could also make this distinction even more complex [1]. As the influence of PAPE response is highly subjective and there is a substantial

Table 1. Summarized effects of PAP and PAPE according to multiple factors

	PAP/PAPE factors	↑ PAP/PAPE effect	↓ PAP/PAPE effect
Athlete characteristics	Training experience	Subjects with **more years of weightlifting experience** [53]	Subjects with **less years of weightlifting experience** [53]
	Gender	In **males** [92,93]	In **females** [92]
	Age	In **adults** [92]	In **youths** [94]
	Fiber type	Subjects with **higher % of type 2 fibers** [1,12,57,58]	Subjects with **lower % of type 2 fibers** [1,12,57,58]
Exercise parameters	Intensity of primer exercise	80-90% of 1 RM [47,75,100-102]	<80% of 1 RM o using body weight [93,100-102]
	Recovery Time	3-10 minutes in **trained** subjects [62,68,70,71]	Still unclear in **untrained** subjects
	Volume of primer exercise	3 sets or **cluster sets** [47,75.76,92]	1 or 2 sets [75]
	Exercise type	**Multiarticular exercises** involving **large muscle masses**: squats, bench press… [60-65]	Still unclear for **monoarticular** exercises involving small muscle masses.
	Conditioning activity	Whether there is a **similarity between primer exercise** and **target exercise** [64]	Whether there is **no similarity** between primer exercise and target exercise [64]
	Range of motion	In exercises that use a **larger ROM** [65-67]	In exercises that use a **smaller ROM** [65-67]
	Type of contraction	Concentric, eccentric, isometric, plyometric and flywheel power modality [85-93]	Isokinetic still unclear.
External factors	Supplement intake	**Caffeine** [103] **or creatine** [101,102] intake	**Carbohydrate** mouth rinse [105]

inter-individual variability, to achieve maximum benefits in terms of strengthening it is essential to consider the individualization of several factors. Athletes with a high level of strength and weightlifting experience, who have a higher proportion of fast twitch fibers and engage in power disciplines, benefit more from the PAP effect [119] than less trained, recreationally active individuals or those oriented towards endurance disciplines with a predominance of slow twitch fibers [119]. This disparity is further accentuated when comparing athletes with sedentary individuals. The specificity of the activity following the conditioning activity can influence the expression of the PAP phenomenon. The greater the similarity on a biomechanical level between the conditioning activity and the subsequent activity, the greater the likelihood of potentiation [65]. For example, a conditioning activity such as the back squat has a better PAPE effect when verified with the CMJ as a target exercise. Likewise, or push-ups with sleds have a better PAPE effect when verified with sprints [64]. The joint excursion of the joints involved in the movements performed as a conditioning activity must also be close to that required in the subsequent performance to maximize the PAPE effect [67–69]. The recovery time between the conditioning activity and the verification test is crucial. In general, full or slightly prolonged recovery is recommended. The time varies with the intensity of the conditioning activity: low-impact plyometric activities require shorter times (2-4 minutes), whereas increasing intensities require longer recoveries (6-12 minutes) for optimal benefits [70–74]. The volume of the conditioning activity (sets x repetitions) is also an important factor [10,24,74–76]. However, in the literature we are currently lacking a standard for the ideal volume, as investigations have used variable approaches. Consequently, further research is required to determine the right volume amount based on the type of athlete tested. In general, higher volumes may cause greater fatigue, requiring longer recoveries. Clustered series configuration has become more efficient than traditional series, and multiple series offer superior advantages over single series [76]. Regarding the type of conditioning activity, isotonic, isometric, plyometric, and ballistic activities have been shown to enhance subsequent explosive strength performance [77–93]. However, there is still no consensus on the best type of load, as several studies have produced conflicting results due to differences in volumes, athletes' experience, intensity, and exercises proposed as conditioning activities. The scientific literature provides limited information on age and gender factors, although the few available studies indicate that both sexes can benefit from PAP. However, male subjects tend to experience greater strengthening effects. This trend is also found in younger subjects, with boys achieving more pronounced effects than girls [94–97,120]. Regarding the intensity of the conditioning activity, high-intensity exercises are more likely to induce the strengthening phenomenon. For traditional weight exercises such as squats or

flat bench presses, heavy loads of 85-100% of 1-RM are more effective than loads of 65-80% of 1-RM. For power lifts or their derivatives, loads of 75-85% of 1-RM are ideal for maximizing PAPE [98–102]. Regarding the ingestion of substances, it has been observed that some substances can increase maximal strength and reduce the time of occurrence of PAPE. In particular, creatine intake seems to increase maximal strength and reduce the onset of potentiation between the conditioning activity and the verification test [103,104]. Some research has claimed that caffeine intake increases potentiation irrespective of recovery time [105], while other research does not support this claim [106]. Furthermore, it has been noted that carbohydrate flushing does not affect post-activation potentiation [107].
Although the in-depth analysis of the literature conducted in the present review has provided exciting insights for future studies, some limitations must be highlighted. In particular, the misuse of the terms PAP and PAPE by many authors needs to be overcome to determine the mechanisms underlying the different phenomena. The term PAPE, proposed by Cuenca-Fernández et al., should be used instead of the overused term PAP, considering the taxonomic rules proposed by Boullosa et al. [18]. Furthermore, the use of multiple protocols with different types of warm-ups makes it difficult to compare results; hence, there is a clear need for more standardization and the analysis of many variables.

Practical Applications and Conclusions

Given that PAP has a very individualized effect, coaches can do their own personal assessments with their athletes to confirm whether they are responders, non-responders, negative responders, or even inconsistent responders [121]. Moreover, it is imperative to consider multiple factors while maximizing its practical implementation. Regarding athlete characteristics, more experienced weightlifters and athletes who are very strong gain more from the PAP effect than less experienced or weaker athletes. Age and gender also may influence the extent of potentiation, with mature male subjects tending to experience greater effects than younger ones. Exercise parameters should be adapted to enhance PAP and PAPE effects. The amount of gain of the PAP phenomenon is influenced by the similarity between the action of the conditioning activities and the action of the verification test; higher similarity induces stronger expression. The recovery time between exercises is also important, and it should be longer for higher intensities and shorter for low-impact plyometric exercises. The volume and type of conditioning activity are also decisive, with cluster sets offering superior benefits. The intensity must be greater than 80% of 1-RM with a volume of three sets to increase the likelihood that the phenomenon will be induced. Finally, the ingestion of substances, creatine and caffeine can contribute to reducing the time of PAP occurrence (creatine) and increase gains (caffeine). In conclusion, both practitioners and researchers should evaluate each factor that interacts with PAP and PAPE individually to ensure the most appropriate conditioning activity for their athletes.

Ethical Committee approval

There is no Ethics Committee declaration, as this is a narrative review.

ORCID

Eugenio Formiglio ID http://orcid.org/0009-0009-9257-7539
Alessandro Tamassia ID http://orcid.org/0009-0003-3605-8001
Eneko Fernández-Peña ID http://orcid.org/0000-0002-4407-5376
Valerio Giustino ID http://orcid.org/0000-0002-4575-8021
Domenico Savio Salvatore Vicari ID http://orcid.org/0009-0003-0568-9812
Antonino Patti ID http://orcid.org/0000-0003-3753-5191
Marco Gervasi ID http://orcid.org/0000-0001-7112-1780

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Corresponding information:
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Correspondence to: *Prof. Eneko Fernández-Peña PhD
University: Department of Physical Education and Sport, University of the Basque Country UPV/EHU, 01007 Vitoria-Gasteiz, Spain), Lasarteko atea, 71 01007 Vitoria-Gasteiz, Spain
E-mail: eneko.fernandezp@ehu.eus