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# EFFECTS OF POSTACTIVATION POTENTIATION WARM-UP ON SUBSEQUENT SPRINT PERFORMANCE: A SYSTEMATIC REVIEW

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**ABSTRACT**

**This review aimed to determine whether a Post Activation Potentiation (PAP) warm-up contributes to an improved sprinting performance. A literature search on 3 databases (PubMed, Scopus and SportDiscus) was conducted on January 30 and 31, 2019. After analysing 115 resultant articles, studies were included if they met the following inclusion criteria: a) studies measured the effects of a PAP intervention, b) PAP was used as a warm-up strategy, c) studies tested exclusively sprint running performance and d) participants were not enrolled in team sports. 11 studies met the inclusion criteria. The results of this systematic review suggest that a PAP warm-up can lead to a significant improvement in running sprint performance, especially in short races (≤40-m). Regardless of the distance, improvements varied mostly between 1.2% and 2.2% of sprint time reduction. However, the large number of modulating factors affecting PAP have concluded in a plethora of opposing results. By reason of this controversy, stating accurate and general guidelines can be unpractical. Nonetheless, athletes and coaches could find this review interesting so as to gain some expertise about the topic, and therefore, try to apply the PAP individually on warm-ups.**

**KEYWORDS**

**PAP, sprinters, running, power, strength, plyometric**

## INTRODUCTION

Post Activation Potentiation (PAP) refers to the enhanced neuromuscular condition observed after the execution of an intense exercise, which results in acute improvements in muscle power output, and therefore, in greater performance on explosive activities (Lim & Kong, 2013; Linder et al., 2010). Considering that power-based movements such as jumping or sprinting are essential in a wide range of sports, the application of PAP as a part of warming up could be key at improving competition performance (Guggenheimer, Dickin, Reyes & Dolny, 2009). Moreover, the more importance power has on the sport, the more an athlete could benefit from the hypothetical enhanced muscle state achieved through PAP. That is why there is a growing interest among Track and Field coaches to be able to apply this technique into their traditional warm-up (DeRenne, 2010).

Nowadays, a traditional warm-up includes low intensity aerobic activity, such as jogging, dynamic stretching and sport specific drills. Its goal is primarily to heighten body temperature, what in fact improves the speed of nerve impulses (Bishop, 2003). Nevertheless, static stretching is still used while warming up, despite having been scientifically proved to cause a decrease in performances dependent on power, force and speed. Mechanical factors of the muscle and neural factors such as a change of the motor strategies may be responsible for this negative affectation. Indeed, it is said that a rigid musculotendinous system can lead to an improvement in power production (Wilson, Murphyi & Pryori, 1994). So, if static stretching is removed and in its place a PAP intervention is included, twitch contraction and rate of force development could be considerably improved, and consequently, sport performance (Hodgson, Docherty & Robbins, 2005; Tillin & Bischop, 2009).

Currently, several types of PAP protocols are applied in order to achieve acute muscular gains. The most used ones are heavy-resistance exercises, with loads exceeding 85% 1 repetition maximum. Back-squat sets are broadly used, probably due to the heavy loads athletes are able to lift (Maloney, Turner & Fletcher, 2014). Yet, there is no need to apply so much external weigh in order to perform an intense movement. In fact, more sport-specific exercises such as plyometrics are claimed to augment power output too, as intensity is reached not only by force, but also by velocity of movement (Healy & Comyns, 2017).

Whatever protocol is used, Post Activation Potentiation is grounded in two principal mechanisms: the phosphorylation of the myosin regulatory light chains and the increased recruitment of higher motor units. The first one refers to the better sensibility of the actin-myosin myofilaments to $Ca^{2+}$ released from the sarcoplasmic reticulum, which facilitates the muscle contraction (Aagaard, Simonsen, Andersen, Magnusson & Dyhre-Poulsen, 2002; Greenough, 2017). The second one makes reference to an enhanced neural activity, and consequently, an improvement in the synchronization of motor units, a decrease in presynaptic inhibition and an increase in central nerve impulses, resulting in a boost in fast twitch muscle fiber contribution (Tillin & Bischop, 2009; Xenofondos et al., 2010). However, there is also evidence that a change in pennation angle may also contribute to PAP. Formed by muscle fascicles and its aponeurosis, the pennation angle affects the force transmission from the muscle to the tendons and bones. A decrement of it, as a result of PAP protocol, may conclude in a more direct transmission of the force, and therefore, an increase in strength (Tillin & Bischop, 2009).

Physiological mechanisms notwithstanding, there is a large number of modulating factors by which PAP does not have the same effect on everybody. To start with, potentiation mechanisms work better in subjects with a high rate of type II motor units. This is because these fibers have a better phosphorylation capacity of light chain myosin as well as a higher velocity of nerve impulse conduction (Hamada, Sale, MacDougall & Tarnopolsky, 2000). Consequently, considering the relationship between strength and fast twitch ratio, it can also be stated that PAP may contribute in a more significant way to stronger athletes (Tillin & Bischop, 2009). Subject´s age affects too, as type II fiber percentage decreases while aging, whereas children, before maturity, lack in strength so as to benefit from PAP (Arabatzi et al., 2014; Poulos, Kuitunen & Buchheit, 2011). Another factor possibly altering PAP may be the power strength ratio. It appears that the less effective an athlete is to convert strength into power, the more he or she would profit from PAP protocols (Tillin & Bischop, 2009). Moreover, people with a high training level may respond more to PAP than amateur athletes due to their ability to recruit faster motor units and their developed fatigue resistance (Chiu et al., 2003). Keeping this all in mind, it can be suggested that high level athletes are more susceptible to realising Post Activation Potentiation than recreationally active people.

But subject related factors are not the only ones modulating the effect of potentiation. Instead, the way a PAP protocol is carried out may influence the most. The type of exercise used, volume, intensity, specificity and rest between protocol and the subsequent performance must be exactly designed so as to reach the desired potentiated state. Current researchers have found that any type of contraction may be likely to activate PAP. Yet, in isometric contractions, a larger number of motor units are activated rather than in dynamic contractions (Tillin & Bischop, 2009). Nevertheless, an isometric exercise would lack in specificity to the following activity, so that it may not be useful (Creekmur, Haworth, Cox & Walsh, 2017). Consequently, back-squat is the most used exercise aiming to elicit PAP, even though Bulgarian split squats, power cleans, sled pushes or plyometrics appear to be biomechanically closer to running (Guggenheimer et al., 2009; Lockie, Murphy, Schultz, Knight & Janse, 2012; Speirs, Bennett, Finn & Turner, 2016). In addition, the rest taken is key, as fatigue coexists with potentiation after a PAP protocol. The maximum potentiation is reached at the same time as maximum fatigue. However, fatigue dissipates faster, so that the point in which there is more potentiation comparing to fatigue would lead to the maximum improvement in performance (Sale, 2002; Tillin & Bischop, 2009).

Track and field athletes competing in modalities such as short sprints may benefit from a PAP based warm-up due to the importance of power in their performances. Thus, the aim of this systematic review is to analyse the effects of different PAP warm-up strategies on the improvement of performance in subsequent sprints.

## METHODS

***Literature Search.*** **The literature selection was conducted on January 30 and 31, 2019. It was carried out through an extensive search of online data bases including PubMed, SportDiscus and Scopus. The following keywords, combined with Boolean operators (AND/OR), were used: "post activation potentiation" OR "postactivation potentiation" AND "sprint". A total of 115 articles were initially extracted form the search after removing repeated researches. By the reading of titles and abstracts, 30 articles were excluded as they were considered irrelevant for the review. This way, 85 papers remained eligible.**

***Inclusion Criteria.*** **Papers were eligible for further study providing that the following inclusion criteria were met: Studies measuring the effects of a PAP intervention, studies applying PAP as a warm-up strategy, studies testing exclusively performance in running sprints and subjects being athletes not enrolled in team sports. A total of 11 researches were found to meet inclusion criteria. The flow chart of search strategy and selection of articles is shown in Figure 1.**

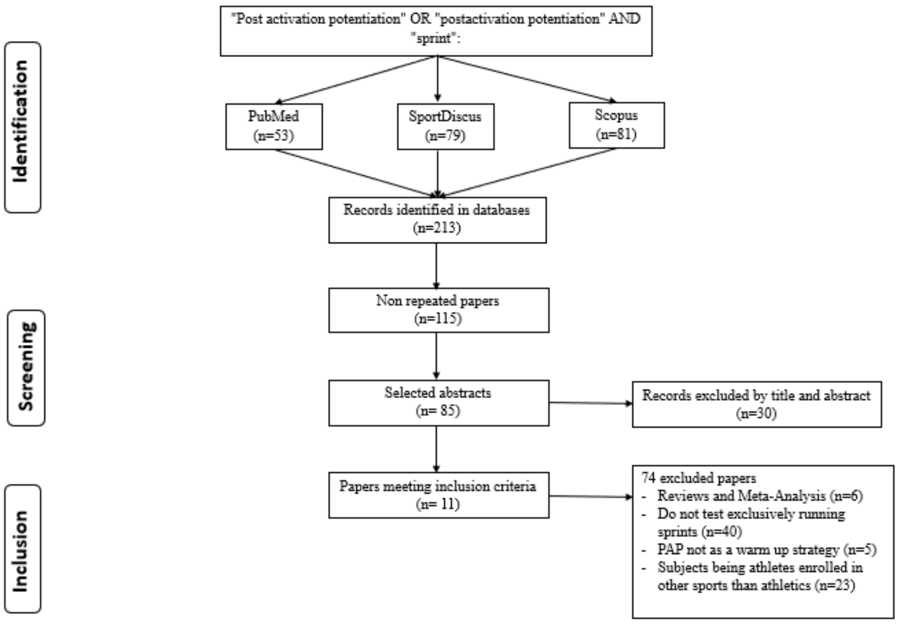


**Figure 1. Flow chart of research strategy and articles selection.**

***Study Quality.*** **To evaluate the methodological quality of the studies included in this systematic review, Oxford´s level of evidence (Oxford Centre for Evidence-based Medicine, 2009) and the Physiotherapy evidence Database (PEDro) (de Morton, 2009; Maher, Sherrington, Herbert, Moseley & Elkins, 2003) scales were selected. Oxford´s level of evidence scale ranges researches from 1 to 5, being 1a attributed to systematic reviews (with homogeneity) of randomized controlled trials and 5 to expert opinion without explicit critical appraisal. According to this, 6 out of the 11 included studies had an evidence level 1b, whereas the remaining 5 scored a 2b level, as a consequence of lacking confidence interval or because less than the 80% of the participants completed the protocol.**

**The PEDro scale consists of 11 items relating scientific rigor. Given that it is impossible to blind participants and that assessors are likewise seldomly blinded in supervised exercise interventions, items 5-7 were excluded. 1 point is awarded for fulfilling each item, so that an 8-point score would mean the maximum research quality. The studies used in this review ranged from 5 points to 8 points in this scale, with a resulting average of 7.54. Studies quality´s evaluation is shown in Table 1.**

***Table 1. Physiotherapy evidence database (PEDro) ratings and Oxford evidence levels of the included studies. ****

| Study | 1 | 2 | 3 | 4 | 8 | 9 | 10 | 11 | Total | Evidence level |
|---|---|---|---|---|---|---|---|---|---|---|
| Creekmur et al. (10) | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 8 | 1b |
| Guggenheimer et al. (17) | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 8 | 2b |
| Harmanci & Karavelioglu (19) | 0 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 7 | 1b |
| Huerta et al. (22) | 1 | 0 | 0 | 0 | 1 | 1 | 1 | 1 | 5 | 2b |
| Lim & Kong (26) | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 8 | 1b |
| Linder et al. (28) | 1 | 1 | 1 | 1 | 0 | 1 | 1 | 1 | 7 | 2b |
| Lockie et al. (30) | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 8 | 1b |
| Poulos et al. (37) | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 8 | 2b |
| Smith et al. (42) | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 8 | 2b |
| Turner et al. (45) | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 8 | 1b |
| Vanderka et al. (47) | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 8 | 1b |
| Total | | | | | | | | | 7.54 | |

***Items in the PEDro scale: 1 = eligibility criteria were specified; 2 = subjects were randomly allocated to groups; 3 = allocation was concealed; 4 = the groups were similar at baseline regarding the most important prognostic indicators; 8 = measure of at least one key outcome were obtained from more than 85% of the subjects initially allocated to groups; 9 = all subjects for whom outcome measures were available received the treatment or control condition as allocated or, where this was not the case, data for at least one key outcome was analysed by "intention to treat"; 10 = the results of between-group statistical comparisons are reported for at least one key outcome; 11 = the study provides both point measures and measures of variability for at least one key outcome. Evidence levels in the Oxford scale: 1a = systematic reviews of randomized controlled trials; 1b = individual randomized controlled trials (with narrow confidence interval); 1c = all or none randomized controlled trials; 2a = systematic reviews of cohort studies; 2b = individual cohort study or low quality randomized controlled trials; 2c = outcomes research; 3a = systematic review of case control studies; 3b = individual case control study; 4 = case series; 5 = expert opinion without explicit critical appraisal, or based on physiology.**

## RESULTS

**All the studies researched in this systematic review had the same scientific purpose: to analyse the effects of a PAP protocol on sprint performance. Though, the interventions applied can be categorised into different groups depending on the exercise or technique used. This way, the 11 studies have been divided into three categories: studies applying heavy-resistance dynamic exercises, studies using plyometric exercises and studies using alternative methods.**

- **Heavy-resistance dynamic exercises**

**Resistance exercises are generally the most employed method in order to reach the desired potentiated state. Huerta et al. (2016) examined the influence of a PAP protocol of back-squats on subsequent 30-meter sprints performance. This protocol consisted of 4 sets of 5 repetitions at 30% 1RM + 4 repetitions at 60% 1RM, 15 seconds before a set of 3 short sprints separated by 120 seconds between them. The control protocol was composed by a single set of 4 repetitions at 60% 1RM previous to a set of 3 short sprints too. 30-meter sprint times showed significant improvement in those athletes performing the 4 experimental sets comparing to those performing control protocol. The decrease of an average of 0.33 seconds was attributed to the potentiation achieved by the PAP protocol.**

Linder et al. (2010) investigated the effects of a single set of 4 repetitions of parallel back half squats at 4RM, with athletes approaching failure at the last repetition, on 100-meter running times. This PAP protocol was carried out 4 minutes after running the first 100 race and 9 minutes previous the second 100 sprint. Additionally, all subjects have previously performed a control test which followed almost the same procedure except for the PAP protocol being replaced by a 4-minute active rest. Results stated that mean sprint times decreased significantly (0.19 seconds) from the first sprint to the second in the experimental condition. Meanwhile, times in the control condition remained the same in both sprints.

Harmanci & Karavelioglu (2017) recruited 44 power athletes and divided them into 3 intervention groups: post activation potentiation, static stretching and control groups. Subjects on PAP group performed one set of 5 back-squats at 90% of 1RM, and then rested for 5 minutes. The second group was applied 6 static stretching exercises, which were done twice for 15 seconds each one. They were also given 5 minutes to rest following stretching. The control group, however, did nothing but resting for 5 minutes. Afterwards, every group performed the running-based anaerobic sprint test (RAST), which involves 6 35-meter maximum sprints with 10 seconds of passive recovery between each one. To compare results, all participants had already taken part in the RAST test between 2 and 3 days previously. The research concluded that PAP intervention significantly enhanced repeated sprint performance, while static stretching caused a significant worsening.

However, not every research support resistance exercise as an effective method to realise PAP. Lockie et al. (2017) studied the impact of a single set of 5 Bulgarian split-squats (BSS) at 5RM intensity on subsequent 20-meter sprints at different recovery times, ranging from 15 seconds to 16 minutes. They concluded that the BSS protocol did not enhance significantly sprint performance comparing to control group (4 minutes of passive rest), regardless of the recovery time.  Though, there were some significant correlations between 5RM BSS absolute and relative strength and potentiated sprint performance, suggesting that the strongest athletes got further benefits from the PAP protocol.

Guggenheimer et al. (2009) were the only ones not applying a squat-based exercise in their attempt to reach PAP. Instead, they decided to employ the power clean (PC), as they found it to be more biomechanically specific to running than squat. In spite of their hypothesis, a treatment consisting of 3 repetitions of PC at 90% 1RM performed one minute before a 40-meter sprint did not ameliorate sprint times, comparing to a non-treatment condition of 3 minutes rest.

- Plyometrics

Although warm-up protocols designed to elicit PAP have traditionally employ resistance exercises, especially heavy squats, a growing number of researches suggest that plyometrics may also provide an effective stimulus. Moreover, this type of exercises might be more specific to running performance as they are linked to a more selective recruitment of type II muscle fibers. In addition, the fact of not needing heavy equipment makes them more suitable to be utilised before competition (Maloney et al., 2014).

Creekmur et el. (2017) divided 10 NCAA Division 1 track and field athletes into two protocols: plyometric warm-up (PWU) and control warm-up (CWU). The first one involved 2 sets of 8 plate jumps with a weight of 11.3 kilograms. 3 minutes between sets and 5 minutes after the second set were taken as recovery. The control warm-up included just 8 minutes of rest. Following both warmings, 3 40-meters sprints were executed, each one 5 minutes apart. Results showed a significant decrease in sprint times of an average on 0,068 seconds when the plyometric sets were performed during warm-up.

Turner et al. (2015) also found evidence in favour of the use of plyometrics to elicit PAP. They compared two experimental protocols during warm-up with a control condition. Both interventions included 3 sets of 10 alternate-leg bounds, either with or without a weighted vest of 10% of subject´s body mass. The control condition consisted of 75 seconds of passive rest, what was virtually the same time it took to perform the plyometric sets. Subsequently, 20-meter sprints were completed with recovery times of 15 seconds, 2, 4, 8, 12 and 16 minutes. Results demonstrated that 4 minutes after weighted and non-weighted plyometric sets, subjects significantly increased their 20-meter sprint velocities on an average of 2.3% and 1.4% respectively. In addition, athletes did also significantly improve performance 8 minutes after weighted plyometrics on 2.5 ± 2.8%. It is also worth to remark that 15 seconds following weighted plyometrics, sprint performances were significantly worsened a mean of 1.4 ± 2.5% when compared to control condition.

Along the same lines did Poulos et al. (2011) accomplish their study. However, they used two different PAP protocols varying in exercise volume to compare with a control condition. Participants carried through with a set of 5 30-meter sprints, separated by 6 minutes of recovery. One group performed 3 hurdle jumps (84 cm high) 60 seconds before each sprint, second group did 9 hurdle jumps also one minute before each sprint and the control group just rested passively through the 6 minutes. Comparing all the sprint times, there was no significant evidence of PAP nor with 3 neither with 9 hurdle jumps protocols.

Vanderka et al. (2015) conducted a really interesting study in which track and field athletes and soccer players were involved. Although in this review only track and field athletes are going to be taken into account, this intervention is especially compelling as it evaluates the effects of loaded half-squat jumps on sprint performance. Indeed, this method to release PAP could be considered as an intermediate procedure between back-squats and plyometrics. 12 athletes performed two different sessions in a randomized order. Control session consisted of 2 sets of 2 40-meter sprints before and after 9 minutes of passive rest. The other session was the experimental one, in which 2 sets of 6 repetition squat jumps were carried out between the same sprint runs as in the control session. The loads applied in the squat jumps were previously selected so as each and every individual could develop the maximum power. Time results indicated that athletes significantly improved their acceleration capacity during experimental session (CI = -

**0.062 to -0.03 seconds), while significantly worsened it under control condition (CI = 0.013 to 0.042 seconds). The same happened with maximal running phase, as it was significantly enhanced after squat jump protocol (CI = -0.037 to -0.01 seconds) but worsened after control (CI = 0.015 to 0.061 seconds). Additionally, significant relationships were observed between 40-meter sprint times and squat power.**

- **Alternative methods**

**Even though heavy-resistance and plyometric exercises stand out among others for being the most applied techniques to elicit PAP, this review includes three researches which put into practice some alternative methods. Lim & Kong (2013) compared 3 PAP protocols with a control condition. Maximum voluntary isometric knee extension, maximum voluntary isometric back-squat and dynamic back-squats were the experimental protocols, whereas 4 minutes of sitting rest were given for the control procedure. For the isometric tests, subjects were asked to perform 3 sets of 3-second maximal contractions. On the other hand, participants completed 3 repetitions of dynamic squats at %90 RM. 4 minutes after each protocol, a single 30-meter run was performed, whose result was compared with baseline sprint test in order to find PAP influence. Finally, results showed no significant differences in sprint performance among any of the protocols. Albeit, they observed large between-subject variations after all 3 PAP, meaning that some subjects responded positively to all experimental conditions while others responded exclusively to selected protocols.**

**Smith et al. (2014) tested the efficacy of sled pulling as a warm-up prior to running dash. In both the control and the experimental trials, procedures were similar. All participants performed a standardised warm-up before the first 40-yd sprint. Then, they rested for 4 minutes and completed a 20-yd run. Finally, they rested for another 4 minutes and performed the last 40-yd race. The only difference between both protocols was that in the PAP procedures, the 20-yd sprint was completed pulling a weighted sled, while in the control condition these sprints were unresisted. Experimental trials were carried out three times with either %10, %20 or %30 of body mass serving as**

**sled resistance. In spite of their hypothesis, final 40-yd sprint times showed that no PAP was reached during any protocol. There was no significant difference among the four resistance levels (%0, %10, %20, %30 of body mass) in subsequent sprint times.**

**Another alternative method that could be implemented in the warming up so as to elicit PAP is whole-body vibration exercises. Guggenheimer et al. (2009) conducted a study in which participants completed a traditional warm-up prior to the first 40-meter sprint. Afterwards, they took part in 4 bouts of "high knee" running on a vibration platform under 0, 30, 40 or 50 Hz. Each bout lasted for 5 seconds and subjects were instructed to take a recovery of half a minute between them. After the vibration condition, athletes performed a set of 2 40-meter sprints, 1 and 4 minutes apart, respectively. Results claimed to be no significant decrease in sprint times after any vibration frequency. There was also no significant improvement from the first to the last 40-meter sprints during any intervention, despite the fact that there was an apparent amelioration within the 30 Hz intervention.**

**Due to all of the above, it is right to say that none of the alternative interventions had succeeded in realising PAP on sprint performance, and therefore, it could be stated that the most commonly applied methods to boost sprint performance (resistance exercises and plyometrics) are at the same time the most effective too.**

*Table 2. Characteristics of the studies and the participants. **

| Study | Number | Age | Training level | Training experience | Force | Other characteristics |
|---|---|---|---|---|---|---|
| *Creekmur et al. (10)* | 10 | 19.3 ± 1.25 | NCAA Division 1 | - | - | Only took part sprinters, jumpers and hurdlers. |
| *Guggenheimer et al. (17)* | 14 /9 | 21 ± 3.0 / 20 ± 1.5 | NCAA Division I | 5 years sprinting / 3 years of PC | - | Two separated but similar studies were conducted. |
| *Harmanci & Karavelioglu (19)* | 44 | 22.2 3 ± 1.85 | Power athletes | 5 years | - | Refrained from intense physical activity. |
| *Huerta et al. (22)* | 7 | 25 ± 2.6 | Military athletes | - | - | Restrained from ingesting stimulating substances. |
| *Lim & Kong (26)* | 12 | 22.4 ± 3.2 | National and club level | 12 months | SQ %150 of BM | Subjects were asked to maintain their habits. |
| *Linder et al. (28)* | 19 | 20.8 3 ± 1.9 | Recreational | 1 year | SQ 4RM mean = 137 ± 35 lb | Restrained from lower-body resistance training as well as from taking ergogenic aids. |
| *Lockie et al. (30)* | 7 | 23.4 3 ± 1.51 | Strength trained | 1 year (two times per week) | - | Asked to be familiar with BSS and to maintain their normal physical and nutritional habits. |
| *Poulos et al. (37)* | 8 | 16.6 ± 1.3 | Elite junior sport academy | 1 year of plyometrics | - | - |
| *Smith et al. (42)* | 24 | 18-28 | Anaerobically trained | 6 months | - | Asked to be active (4-6 days/week). |
| *Turner et al. (45)* | 23 | 22 ± 1 | Non-competitive | At least 2 years. Mean = 5 ± 1 years | - | Restrained from caffeine, alcohol and strenuous exercise. |
| *Vanderka et al. (47)* | 12 | 16 – 18 | Regional level | 3 years | - | The ingestion of alcohol and caffeine were prohibited. |

*SQ = squat; BM = body mass; NCAA = national collegiate athletic association; RM = repetition maximum; PC = power clean; BSS = Bulgarian split squat.

*Table 3. Characteristic of the training programs. **

| *Study* | *experimental protocol* | *Control protocol* | *Rest before performance* | *Measured performance* | *Outcomes* |
|---|---|---|---|---|---|
| *Creekmur et al. (10)* | 2x8/3´ PJ | 8´ rest | 5´ | 3x40m/5´ sprints | Significant decrease in sprint times when plate jumps were performed. |
| *Guggenheimer et al. (17)* | -4x5s/30´´ HNVR: 30, 40 or 50 Hz<br>-1x3 (90%) PC | - 4x5s/30´´ HNR<br>- 3´ rest | 1´ | 2x40m/3´ sprint | No significant improvement was found between the first and the last sprint times across all vibration frequencies.<br>No significant difference between control and PC treatment trials for sprint times. |
| *Harmanci & Karavelioglu (19)* | -2x15´´ 6 SS<br>-1x5 (90%) SQ | 5´ passive rest | 5´ | 6x35m/10´´ sprints (RAST) | Significant improvement in RAST test was found after back-squat protocol.<br>Significant worsening was observed in RAST test after Static Stretching. |
| *Huerta et al. (22)* | 1x5 (30%)<br>1x4 (60%)<br>SQ | 1x4 (60%) SQ | 15´´ | 3x30m/2´ sprints | Significant decrease in 30-meter sprint times between the control set and the experimental sets. |
| *Lim & Kong. (26)* | -3x3s/2´ IKE<br>-3x3s/2´ ISQ<br>-1x3 (90%) SQ | 4´ sitting rest | 4´ | 1x30m sprint | No significant difference in sprint performance among control, isometric knee extension, isometric squat or dynamic squat protocols. |
| *Linder et al. (28)* | 1x4 - 4RM/2´ SQ | 4´ walking rest | 9´ | 1x100m sprint | A significant mean improvement in sprint times when preceded by PAP intervention. |
| *Lockie et al. (30)* | 1x5 - 5RM BSS | 4´ sitting rest | 0´, 2´, 4´, 8´, 12´ and 16´ | 20m sprints | No significant effects for the PAP conditions. |
| *Poulos et al. (37)* | -3 HJ<br>-3x3/10´´ HJ | 6´ rest | 1´ | 5x30m/6´ sprints | No significant effect was found for neither a condition nor a set. |
| *Smith et al. (42)* | 20-yd RS with 10, 20 or 30% of athlete´s BM | 20-yd sprint | 4´ | 1x40-yd sprint | Significant main effect difference in pre and post 40-yd sprint times.<br>No significant differences among loads of 0, 10, 20 and 30% of athlete´s body mass. |
| *Turner et al. (45)* | -3x10 P<br>-3x10 WP with 10% of BM | 75´´ walking rest | 0´, 2´, 4´, 8´, 12´ and 16´ | 20m sprints | 10m times were significantly improved after 4 minutes during P and after 8 minutes during WP.<br>20m times were significantly reduced after 4 minutes during both P and WP and after 8 minutes during WP. |
| *Vanderka et al. (47)* | 2x6/3´ WJSQ (power max) | 9´ sitting rest | 4´ | 2x40m/3´ sprints | Significant improvement in 40-m sprint times after experimental condition. There was also a significant worsening after control protocol. |

*SQ = squat; WJSQ = weighted jump squat; IKE = isometric knee extension; ISQ = isometric squat; PJ = plate jump; RM = repetition maximum; P = plyometric; WP = weighted plyometric; BM = body mass; BSS = Bulgarian split squat; RS = resisted sprint; HNVR = high knee vibration running; HNR = high knee running; PC = power clean; HJ = hurdle jump; SS = static stretching.

## DISCUSSION

The current study intended to perform a systematic review to find out the influence of PAP-based warm-ups on sprint performance. The main finding was that despite all controversy caused by opposing results, Post Activation Potentiation is a physiological enhancement that can lead to a significant decrease in subsequent sprint times.

These improvements were principally seen in short races (≤40-m), although it has also been proved that 100-meter runs can likewise be potentiated through PAP interventions. Regardless of the distance, improvements varied mostly between 1.2% and 2.2% of sprint time reduction (Creekmur et al., 2017; Linder et al., 2010; Smith et al., 2014; Turner et al., 2015; Vanderka et al., 2015). Even if it these percentages sound irrelevant, short sprint performance can swing from excellence to average in a matter of few second hundredths. For instance, if the athlete who ranked seventh in the 60-meter world championship final in 2018 had suffered a potentiation of 1.2% on his performance, he would have reached the fourth place, improving his mark from 6.60 to 6.52 seconds. More surprisingly, Christian Coleman would have beat his own world record with only an improvement of 0,5% on sprint time in that race (World Records [IAAF], 2019). We are not claiming that these elite sprinters would have undergone such an increase in their 60-meter sprint performances, but these examples reflect how an apparently scarce improvement can make the difference in short sprints.

Nevertheless, there are still countless athletes which continue warming-up through traditional methods, including sometimes static stretching, which has already been proved to reduce subsequent force output. As Harmanci & Karavelioglu (2017) proved, a traditional warm-up involving an aerobic exercise such as jogging is significantly less effective than a PAP warm-up in order to enhance performance in succeeding sprints.

Moreover, if static stretching's are added to this traditional warm-up, not only is our muscular ability not potentiated, but it is also worsened as muscle and neural properties such as reflex sensitivity are impaired. Having stated that, it is clear that encouraging sprinters and their trainers to employ PAP in their warm-ups could be key, as it would also suppose putting aside warming techniques which are both ineffective and detrimental for sprint performance (Cramer, Housh, Johnson, Miller & Coburn, 2004).

Despite having no doubts that eliciting a potentiated state can help to reach higher athletic performances in short sprints, PAP is a far more complicated phenomenon, as the diverse and sometimes opposing scientific results demonstrate. It seems to be clear that depending on some factors, athletes are more or less prone to benefit from it (Seitz & Haff, 2016; Tillin & Bischop, 2009; Xenofondos et al., 2010). To start with, there is evidence to suggest that the stronger an athlete is, the more he or she could benefit from PAP, as they tend to have a higher average of type II muscle fibers, and consequently, a higher phosphorylation capability. This has been proved in several studies (Gourgoulis, Aggerloussis, Kasimatis, Mavromatis & Garas, 2003; Kümmel et al., 2016), where correlations between muscular strength and potentiation rate were reported. Albeit, only two of the researches employed in this review measured the strength of their participants. Lim & Kong (2013), conclude that no potentiation was reached during no one of the interventions even though athletes were requested to be able to squat at least 1.5 of their body masses. On the contrary, Linder et al. (2010) carried out a research in which recreational subjects were involved. Even if their repetition maximal squats were not as heavy, they underwent improvement after PAP protocol in 100-meter sprint times. For all this, we conclude that even though force level affects to the potentiation level, there are other factors, not related to subjects, that might influence more.

The type of exercise applied in the warm-up and primarily how specific it is to the subsequent activity can modulate PAP. Neither isometric nor vibration-based protocols have been successful in enhancing sprint performances (Guggenheimer et al., 2009; Lim & Kong, 2013). In contrast, 60% of the studies making use of heavy-squats managed to better sprint times (Harmanci & Karavelioglu, 2017; Huerta et al., 2016; Linder et al., 2010). This percentage raises to 75% if we refer to plyometric protocols (Creekmur et al., 2017; Turner et al., 2015; Vanderka et al., 2015). However, sled pulls seem to be the most specific exercises to running, but in this case, Smith et al. (2014) founded no significant differences between none of the sled weights and the control condition. This could have happened because the control condition involved a non-weighted running, what might release PAP too. In fact, Winwood et al. (2016) concluded that pulling a 75% of body mass sled can lead to subsequent sprint speed improvement if an appropriate rest (8-12 minutes) is taken.

So, recovery time is apparently a crucial factor that must be correctly specified. It widely depends on the relationship between fatigue and potentiation (Sale, 2002; Tillin & Bischop, 2009). This way, if the warm-up exercise causes a great deal of fatigue, the recovery until performance will be larger than after a less exhausting exercise. Nevertheless, if too much rest is taken, the potentiation effect will also disappear. As a result, we have concluded that it is senseless to concrete a specific time in which PAP works the best. In fact, while Huerta et al. (2016) achieved the desired potentiated state just 15 seconds after the squat sets, Turner et al. (2015) did not achieve any improvement until 8 minutes passed during the weighted plyometric protocol. Other researches have succeeded in eliciting PAP on sprint performance with recovery times ranging from 1 to 15 minutes, with no apparent differences between those employing heavy-resistance dynamic exercises and those using plyometric exercises (Byrne, Kenny & O´Rourke, 2104; Chatzopoulos et al., 2007; Lima et al., 2011; Matthews, Matthews & Snook, 2004; McBridge, Nimphius & Erickson, 2005; Winwood et al., 2016; Xenofondos et al., 2010). Regarding the time an athlete usually must wait between the warm-up and the competition, we consider that PAP results practical when the potentiation appears at least 8 minutes afterwards.

More or less the same happens if we refer to exercise volume or intensity. Both are in a great extent dependent on subject characteristics, recovery time and nature of the subsequent activity. Two out of the three successful studies measuring the effects of heavy back-squats in this review, applied a near maximal intensity (%90 of RM and 4RM) (Creekmur et al., 2017; Harmancy & Karavelioglu, 2017). Supporting this notion, McBride et al. (2005) achieved an improvement of %0,87 in 40-meter sprint times after a set of back-squats at %90 of 1RM. Similar results showed Bevan et al. (2010), as they managed to reduce 5- and 10-meter sprint times by performing a set of three repetitions of back-squat at %91 of 1RM. On the other hand, Huerta et al. (2016) reached positive outcomes by using %30 - %60 of 1RM intensities. In any case, the vast majority of the researches verifying PAP employed a back-squat intensity higher than %70 of 1RM (Bevan et al., 2010; Chatzopoulos et al., 2007; Evetovich, Conley & McCawley, 2015; Low, Harsley, Shaw & Peart, 2015; Matthews et al., 2004; McBridge et al., 2005; Rahimi, 2007; Seitz & Haff, 2016; Yetter & Moir, 2008).

This topic becomes less controversial when plyometric exercises are applied, as it seems that any plyometric activity is by itself intense. Although, it may be more effective if maximum power production is reached, and consequently, additional loads may be necessary (Gilbert & Lees, 2005). Poulos et al. (2011) investigated the effects of unweighted plyometrics on subsequent sprint performance, with no significant results. To the contrary, Vanderka et al. (2015) achieved significant increasements in 40-meter sprint velocity after two sets of 6 jump squats with the load resulting in maximum power output. Analogous results showed Creekmur et al. (2017), also employing 2 sets of weighted plyometrics. Nevertheless, Turner et al. (2015) demonstrated that PAP can be released by both weighted and unweighted plyometrics, merely varying the recovery time. This controversy is also expressed in other researches, with positive and negative attempts to elicit PAP on sprint performance using any type of plyometric activities (Byrne et al., 2014; Kümmel et al., 2016; Lima et al., 2011; McBridge et al., 2005).

Finally, exercise volume is equally heterogeneous among studies gathered in this review. The three successful back-squat protocols used four, five and nine repetitions respectively. Besides, there is no evidence to state that more volume is added when the intensity lower is (Harmancy & Karavelioglu, 2017; Huerta et al., 2016; Linder et al., 2010). With plyometrics, however, it seems that a higher number of repetitions is needed. Poulos et al.

(2011) was the only research in which less than a total of 10 repetitions were applied, and therefore, it is the only study failing to elicit PAP through plyometrics. Still, Byrne et al. (2014) proved that it is likewise possible to reach potentiation by a unique set of 3 depth jumps. Once again, scientific researches conclude that it is pointless to give accurate guidelines in order to potentiate sprint performance by carrying out the ideal warm-up.

In summary, in spite of the controversy shown by opposing scientific outcomes, we have no doubts that Post Activation Potentiation is a physiological condition that an athlete can take advantage of. Depending on the exercise, the volume, the intensity, the athlete´s characteristics, the subsequent activity and the recovery time, the potentiation effect will vary, and so will fatigue do too. For that reason, we have come to the conclusion that PAP should be considered as an individual phenomenon, which can be of great value for a sprinter if an appropriate and personalised warm-up procedure is followed.

## PRACTICAL APPLICATIONS

The results of this systematic review suggest that a Post Activation Potentiation warm-up can lead to a significant improvement in running sprint performance. Considering the eleven studies employed, we could recommend a warm-up protocol including 12 to 16 weighted plyometric repetitions at power maximum intensity, with 8 to 15 minutes of recovery, but it would not work for everyone. Instead, we recommend any sprinter and corresponding trainers to test different PAP strategies, until they found the one that suits better. Changing the way an athlete warms up can be key to succeed in sprint competitions, and that is why we claim that it is worth introducing PAP into athletic routines.

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