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Human Kinetics
BRIEF REVIEW

Current Evidence and Practical Applications of Flywheel Eccentric Overload Exercises as Postactivation Potentiation Protocols: A Brief Review

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Purpose: To summarize the evidence on postactivation potentiation (PAP) protocols using flywheel eccentric overload (EOL) exercises. ***Methods:*** Studies were searched using the electronic databases PubMed, Scopus, and Institute for Scientific Information Web of Knowledge. ***Results:*** In total, 7 eligible studies were identified based on the following results: First, practitioners can use different inertia intensities (eg, 0.03–0.11 $kg{\cdot}m^2$), based on the exercise selected, to enhance sport-specific performance. Second, the PAP time window following EOL exercise seems to be consistent with traditional PAP literature, where acute fatigue is dominant in the early part of the recovery period (eg, 30 s), and PAP is dominant in the second part (eg, 3 and 6 min). Third, as EOL exercises require large force and power outputs, a volume of 3 sets with the conditioning activity (eg, half-squat or lunge) seems to be a sensible approach. This could reduce the transitory muscle fatigue and thereby allow for a stronger potentiation effect compared with larger exercise volumes. Fourth, athletes should gain experience by performing EOL exercises before using the tool as part of a PAP protocol (3 or 4 sessions of familiarization). Finally, the dimensions of common flywheel devices offer useful and practical solutions to induce PAP effects outside of normal training environments and prior to competitions. ***Conclusions:*** EOL exercise can be used to stimulate PAP responses to obtain performance advantages in various sports. However, future research is needed to determine which EOL exercise modalities among intensity, volume, and rest intervals optimally induce the PAP phenomenon and facilitate transfer effects on athletic performances.

Keywords: warm-up, power, sprint, training, jump

This review summarizes the current evidence regarding postactivation potentiation (PAP) strategies using flywheel eccentric overload (EOL) exercises. The first section covers the PAP phenomenon, its underpinning neurophysiological mechanisms, and commonly used PAP protocols. The second section describes the characteristics of flywheel ergometers and the rationale for using EOL to induce PAP effects. The third section summarizes the growing literature, which has evaluated the onset, time course, and magnitude of PAP effects on athletic performance using EOL exercises. Finally, this review reports some practical recommendations on how PAP effects can be elicited using EOL exercises in applied settings and proposes future research directions.

Postactivation Potentiation

PAP is defined as "the phenomena by which muscular performance characteristics are acutely enhanced as a result of their contractile history."[1–3] This term is generally used when the enhanced muscular response following a potentiation activity can be verified with a twitch interpolation technique.[2,4,5] However, among sport scientists and coaches, PAP is commonly interpreted as an enhancement of athletic performance measured in voluntary exercise requiring rapid or maximal force production.[3,6] Two underpinning pathways are thought to account for the PAP effects: peripheral and central. Myosin regulatory light chain phosphorylation is suggested to be the main peripheral mechanism associated with PAP. The augmented phosphorylation of regulatory light chain is mediated via the enzyme myosin light chain kinase, which leads to a greater rate of cross-bridge attachment.[1,7,8] This is due to an increased sensitivity of the contractile proteins to calcium (Ca^{2+}), which is released from the sarcoplasmic reticulum.[3,9,10] This mechanism facilitates the force and rate of force development of low- and high-frequency contractions.[11,12]

PAP may also result from spinal and supraspinal pathways. It is speculated that increases in synaptic efficiency induced by residual elevation of presynaptic Ca^{2+} and decreases in transmitter failure occurring at higher order motoneurons are responsible for fast-twitch motor units.[13,14] These central effects may contribute to a sustained recruitment of higher threshold motor units and increases in fast-twitch fiber contribution to muscular contraction.[15] However, a recent review does not support this central explanation underpinning PAP.[2] Hence, it could be concluded that regulatory light chain phosphorylation is considered the primary mechanism for PAP, whereas other influences at the central level remain to be clarified.

Methodological Approaches for PAP Protocol Design

There are a number of variables that need to be considered when designing PAP protocols: type of muscular contraction, time interval between the PAP conditioning activity and subsequent performance test, biomechanical similarities, and intensity of load. PAP methods are commonly classified as either static or dynamic,

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according to the muscular contraction mode of the conditioning activity.[1] Examples of static potentiating protocols include isometric continuous or intermittent maximal voluntary contractions, while dynamic protocols include loaded jumping, sprinting, throwing movements, and resistance exercises.[3] Although both methods can potentiate subsequent athletic performances, they induce dissimilar fatigue and potentiation responses. The different nature of the underpinning PAP mechanisms induced by static and dynamic methods has specific implications for the methodological design of PAP protocols. Static PAP protocols implement volumes (1–5 sets × 3–10 s) of isometric contractions executed at high intensity (>90% maximal voluntary contraction).[16–19] PAP protocols using dynamic contractions require greater volumes and are commonly designed as multiple-set configurations (2–3 sets × 3–8 repetitions) and executed at submaximal intensities (60%–90% 1-repetition maximum).[3,9,20–22]

Another key variable affected by the specific potentiation method is the necessary time interval between the PAP conditioning activity and the subsequent performance test. Although the majority of the PAP studies suggest a recovery interval of 3 to 11 minutes to elicit the greatest PAP effect,[3] the exact PAP onset time and duration vary and depend on the type of the conditioning activity. Isometric contractions evoke PAP earlier (≤3 min) when compared with dynamic conditions,[16,23] which require longer rest intervals (≥3 min).[6] However, PAP effects induced by dynamic protocols persist for longer durations compared with static protocols and can be maintained up to 12 minutes after protocol completion.[1,24] Thus, it is likely that each potentiation complex achieves the PAP via different pathways, affecting the onset, magnitude, and duration of the potentiation effects.[7,13,25] Finally, the contemporary literature recommends practitioners to select conditioning exercises with biomechanical similarity to the subsequent athletic performance intended to improve (eg, squat exercises for jump tasks or hip thrusts for sprint tasks).[15,26–28] Indeed, high kinematic and kinetic specificity seem to play a favorable role in optimizing the potentiation effects.[6,27]

Flywheel Devices and EOL Training

Flywheel ergometers have been present in the scientific literature since the early 20th century.[29] They were developed as resistance training devices for space travelers exposed to nongravity environments and became popular in the early 1990s as a tool for high-intensity resistance training without the requirement for gravitational resistance.[30,31] During the concentric phase, the rotational acceleration of the flywheel develops inertial torque, initially accumulated, and then returned back during the eccentric phase, allowing for repetitive concentric–eccentric cycles.[32] Skeletal muscle is able to develop greater forces during eccentric than concentric activities,[33] and such flywheel exercises can determine a more demanding eccentric phase due to the augmented mechanical load that necessary to absorb the kinetic energy stored in the flywheel and to decelerate it. This is not achievable by performing traditional isotonic weight-lifting exercises.[34–36] As a consequence, flywheel resistance devices allow for maximal force development throughout the full range of motion, with short periods of greater eccentric than concentric force demands. This observation has led to subsequent increased utilization of these devices to obtain acute responses and chronic adaptations (eg, for strength, hypertrophy, power, injury prevention, rehabilitation) in both amateur and professional sporting settings.[9,33,37–40] Moreover, because of the portability of these devices, practitioners can use them outdoors or bring them out from weight rooms, further increasing their practical sporting applications.

Evidence and Hypothesis Supporting EOL Training as a PAP Strategy

EOL training has been consistently used to induce chronic adaptations; however, a few studies have investigated the acute potentiation benefits offered by this exercise modality.[34,41] The rationale for utilizing flywheel EOL protocols to facilitate PAP responses is based on the two (central and peripheral) mechanisms underpinning PAP.[13] EOL actions, as well as eccentric contractions in general, are believed to selectively recruit higher order motor units to a greater extent than concentric contractions.[42–46] This results from higher motor unit discharge rate and synchrony.[1,47] This relatively greater contribution of motor unit activation may be augmented even more during compound multijoint movements, commonly executed during EOL exercises (eg, squat).[48–50] Further advantages of EOL exercises as potentiating activities are the consistently greater eccentric force, power, and derivative outputs produced.[51,52] These greater eccentric kinetic outputs can contribute to improving stretch-shortening cycle performance, which may induce stronger transfer effects on the fast, mixed eccentric/concentric actions of athletic tasks, such as jumps, sprinting, and changing direction.[51,53] These tasks may benefit from the prior execution of EOL exercises that functionally overload the musculotendinous system in a specific manner (eg, eccentric contraction) and with a high degree of similarity in terms of muscle actions and joint kinematics used.[15,26–28]

Current Knowledge Related to EOL Exercise and PAP

Knowledge on the PAP effects of EOL exercises is relatively new to the scientific community. The first investigation on this topic was published in 2014, and 7 studies have examined the PAP effects of EOL exercises on athletic tasks performance to date (Table 1).[9] These studies were identified through searches using PubMed, Scopus, and Institute for Scientific Information Web of Knowledge databases using the following terms: "eccentric overload," "eccentric overload exercise," "flywheel," "iso-inertial," "flywheel resistance," and "postactivation potentiation." In addition, the references of all the identified articles were searched for other relevant articles.

In the selected studies, changes in performance following PAP protocols were calculated as percentage differences (%) using the following formula:

$$\frac{(\text{post} - \text{PAPi} - \text{baseline})}{\text{baseline}} \times 100$$

where i represents any post-PAP assessment time point. Hedges g effect sizes (ESs) were calculated from the original to examine the extent of the PAP effects. Specifically, ESs were determined for each PAP protocol as for within-group analyses and calculated relatively to baseline or control conditions absent of any PAP intervention.

The equation $d = M_{\text{diff}}/S_{\text{av}}$ (M_{diff}, mean difference; S_{av}, average SD) with the adjustment factor of

$$g = \left(1 - \frac{3}{4_{\text{df}} - 1}\right) \times d$$

was used for this purpose.

Table 1 Summary of Studies That Investigated the Postactivation Potentiation Effects of EOL Protocols

Study	Participants and training status	Intervention	Rest interval	Intensity	Findings	Hedges *g* effect size
Beato et al,[34] 2019	12 physically active men	EOL condition 1: 3×6 half squats at M-EOL EOL condition 2: 3×6 half squats at H-EOL (Rev: 2-min passive) or control	30 s, 3 min, and 6 min	Inertia (kg·m^2): M-EOL: 0.029; H-EOL: 0.061	Differences between both M-EOL and H-EOL and control	
					↑ CMJ height post 3 min and post 6 min after M-EOL (8.5% and 10.5%) and H-EOL (10.4% and 11.3%)	M-EOL: 0.5–0.78 (medium); H-EOL: 0.67–0.73 (medium)
					↑ $CMJ_{peak\ power}$ post 3 min and post 6 min after M-EOL (5% and 4.5%) and H-EOL (5.3% and 6.7%)	M-EOL: 0.31–0.28 (small); H-EOL: 0.33–0.38 (small)
					↑ COD—5 m post 3 min and post 6 min after M-EOL (3.5% and 3.1%) and H-EOL (3.4% and 5.2%)	M-EOL: 0.47–0.53 (small to medium); H-EOL: 0.51–0.78 (small to moderate)
					↑ LJ distance post 3 min and post 6 min after M-EOL (6.3% and 8.4%) and H-EOL (6.8% and 7.7%)	M-EOL: 0.47–0.62 (small and medium); H-EOL: 0.50–0.57 (medium)
Beato et al,[6] 2019	18 physically active men	3×6 EOL half squats (Rec: 2-min passive) or control	15 s, 1 min, 3 min, 5 min, 7 min, and 9 min	Inertia (kg·m^2): M-EOL: 0.029	Differences between EOL and control	
					↑ CMJ height post 3 min, post 5 min, post 7 min, and post 9 min (range: 8.0–15.6%)	range: 0.54–0.63 (medium)
					↑ $CMJ_{peak\ force}$ post 5 min, post 7 min, and post 9 min (range: 4.2–5.7%)	range: 018–0.24 (trivial to small)
					↑ CMJ impulse post 5 min, post 7 min, and post 9 min (range: 5.1–5.3%)	range: 0.25–0.26 (small)
					↑ $CMJ_{peak\ power}$ post 1 min, post 3 min, post 5 min, post 7 min, and post 9 min (range: 4.4–8.4%)	range: 0.20–0.42 (small)
					↑ Isokinetic knee extension concentric peak torque (60°/s) at 9 min (3.8%)	0.12 (trivial)
					↑ Isokinetic knee flexion concentric and eccentric peak torque (60°/s) at 9 min (7.7% and 8.2%)	0.22–0.20 (small)
Cuenca-Fernández et al,[56] 2015	14 (10 men and 4 women) trained swimmers	1×4 flywheel half squats or 1×3 lunges at 85% of 1RM or control	8 min	Not reported	Differences between flywheel and control	
					↑ Dive distance (3.4%)	1.09 (large)
					↑ 5-m performance time (5.7%)	2.3 (large)
					↑ 15-m performance time (2.4%)	0.75 (medium)

(continued)

Table 1 (continued)

Study	Participants and training status	Intervention	Rest interval	Intensity	Findings	Hedges *g* effect size
					Differences in responses between lunges at 85% of 1RM and control	
					↑ Dive distance (2.1%)	0.66 (medium)
					↑ 5-m performance time (2.3%)	0.75 (medium)
Cuenca-Fernández et al,[57] 2018	17 men competitive swimmers	1 × 4 lunges and 1 × 4 arm flywheel strokes or 1 × 3 lunges and 1 × 3 arm strokes at 85% of 1RM or control	6 min	Not reported	Differences between flywheel and control	
					↑ Dive velocity (4.3%)	0.32 (small)
					↑ Angle of takeoff velocity (12%)	0.52 (medium)
					↑ 5- to 10-m swimming velocity (7%)	0.54 (medium)
					Differences between lunges at 85% of 1RM and control	
					↑ Angle of takeoff velocity (15.8%)	0.63 (medium)
Cuenca-Fernández et al,[57] 2018	13 (11 men and 2 women) competitive swimmers	1 × 5 flywheel device or control	6 min	Not reported	Differences between flywheel and control	
					↑ Peak vertical force (8.2%) at kick start	0.38 (small)
					↑ Rate force development (15.9%) at kick start	0.21 (small)
de Hoyo et al,[9] 2014	20 young highly trained soccer players	4 × 6 flywheel half squats (Rec: 2-min passive) or control	Not reported	Inertia (kg·m^2) To achieve maximal power outputs (0.11)	Differences between flywheel and control	
					↑ Kinetic measures associated to COD performances using crosscutting task, such as vGRF (33%) and PvGRF (14%)	1.05–1.3 (large)
					↑ CMJ height (6.3%)	0.52 (medium)
					↑ 20-m sprint time (0.7%)	0.16 (trivial)
Timon et al,[59] 2019	16 (9 men and 7 women) physically active students	3 × 6 EOL half squats (Rec: 3-min passive) or 3 × 6 half squat at OPL (Rec: 3-min passive)	4, 8, and 12 min	Not specified but individually determined to achieve maximal power outputs	Differences between EOL and control	
					↑ SJ height post 4 min and post 8 min (6.8% and 7%)	0.33–0.34 (small)
					↑ SJ_{Power} post 4 min and post 8 min (4.5% and 4.3%)	0.18–0.17 (trivial)
					No differences between OPL and control	

Abbreviations: ↑, increase or greater improvement in performance; 1RM, 1-repetition maximum; CMJ, countermovement jump; COD, change of direction; EOL, eccentric overload; H-EOL, high intensity; LJ, long jump; M-EOL, moderate intensity; OPL, optimum power load using barbell; PvGRF, peak vGRF; Rec, recovery; SJ, squat jump; SJ_{Power}, SJ peak power; vGRF, vertical ground-reaction force.

This approach enabled the estimation of unbiased effects and standardized comparisons between protocols. ES were then interpreted as trivial (<0.2), small (0.2–0.5), medium (0.5–0.8), or large (>0.8).[54,55]

Despite the low number of studies, the summary of their results provides preliminary evidence about methodological guidelines for practical applications. PAP protocols designed with flywheel EOL exercises using either single or multiple sets, performed at varying intensities (0.03–0.11 kg·m^2), with brief rest period durations (3–9 min) seem effective to induce PAP effects (Table 1).[6,9,34,56–59] Moreover, the potentiation was found to be of a greater extent on athletic tasks having higher biomechanical similarity with the potentiating EOL exercise.

With regard to the volume of EOL exercise implemented as PAP protocols, both single and multiple sets can induce potentiation resulting in augmented kinetic outputs (eg, force, impulse, power) and enhanced athletic performances (eg, vertical and horizontal jumps, sprints, changes of direction, swimming kick start).[34,56,57] Although no study has specifically compared the PAP effects of different EOL exercise volumes, this review suggests, based on previous PAP literature, possible advantages in protocols using multiple sets compared with a single set.[3] This assumption is supported by the relative greater range of ES on athletic performances reported in studies implementing multiple sets (small to large) compared with those using single-set protocols (small) (Table 1). Based on the contemporary scientific literature, multiple-set protocols seem relatively preferable, though this interpretation must be taken with caution. It is known that even the same PAP conditioning activity and stimulus may induce varying responses between individuals and on different athletic tasks.[3,34]

In contrast to traditional PAP methods, where onset, magnitude, and duration of the potentiation are modulated by the different intensities of the conditioning activity, it seems that consistent PAP effects can be induced by EOL exercises using a broader range of intensities.[3,20,60,61] On one hand, the present review confirms the relationship between fatigue and PAP and confirms the evidence that both are present at PAP protocol completion. In fact, EOL exercises using different inertial loads (eg, 0.03 or 0.06 kg·m^2) initially induce a transient state of fatigue where athletic performance is impaired. However, it is interesting to note that following EOL exercise, PAP outweighs fatigue after relatively short rest intervals (<6 min) regardless of the exercise intensity. In a recent study, Beato et al[34] compared the PAP effects of "moderate" (0.03 kg·m^2) and "high" (0.06 kg·m^2) inertial flywheel half-squat intensities on countermovement jump, long jump, and change-of-direction performance. The authors did not find any difference between the protocols on the onset and magnitude of the resulting PAP effects; thus, concluding that both exercise intensities may be used equivalently.

The present review reconfirms exercise specificity and similarity between the potentiation protocol and the subsequent athletic tasks for exploiting optimal PAP effects following EOL exercises. This assumption is supported by 2 main observations. First, greater potentiation ESs were consistently found on athletic tasks with kinematic characteristics and ground reaction force orientation profiles similar to those of the EOL exercise. Most of the EOL exercises used in the reviewed studies were performed as half-squat movements, which are characterized by a predominant vertical orientation of the associated kinetic (eg, ground reaction force) responses. Therefore, it is not surprising that EOL half squats potentiated vertical-oriented tasks like squat jumps and countermovement jump to a greater extent (small to medium) than horizontal-oriented ones like sprinting (trivial) and change of direction (small).[6,34] Second, similarly greater effects were found on athletic tasks executed as coupled eccentric–concentric movements compared with concentric-only movements or isokinetic actions.[59] Specifically, small to large effects were reported on countermovement jump performance following EOL half squats,[6,9] whereas the same potentiation stimulus and rest intervals only induced trivial to small effects on either swimming kick-start performance[58] or isokinetic concentric knee extension and concentric and eccentric flexion peak torque outputs.[6] These findings support the rationale of prescribing potentiating exercises in which muscle actions and joint kinematic and kinetic profiles are similar to those in the subsequent activity to optimize the PAP effects. Nevertheless, this interpretation must be taken with caution and needs to be further verified as limited literature currently exists on the topic. Future research comparing the PAP effects of horizontal- and vertical-based EOL exercises is needed.

Practical Applications

Implementing EOL exercises is a novel PAP-inducing strategy that can be used by applied practitioners. Until further research is conducted to provide precise evidence-based guidelines, the following preliminary practical recommendations can be suggested. First, EOL using different loads can stimulate similar magnitudes of PAP response; therefore, practitioners may use a broader range of inertial intensities (eg, 0.03–0.11 kg·m^2) to enhance the subsequent athletic performances (eg, countermovement jump, long jump, change of direction). However, greater intensity may be accompanied with greater levels of acute fatigue, which should be considered when planning the rest period between the conditioning stimulus and subsequent activity. Second, the rest period needed following EOL exercises seems to be consistent with the gravitational loading–based PAP literature: Muscular fatigue is dominant immediately following the PAP stimulus (up to 3 min), whereas PAP is dominant in the minutes thereafter (after 3 min). Third, as EOL exercises require large force and power outputs, low volumes (eg, 2–3 sets) of the conditioning activity seems to be a sensible approach. In fact, higher volumes could induce greater acute fatigue and potentially delay or even restrict the onset of the PAP effects on performance. Due to the heavy eccentric muscular strain and the specificity of the EOL exercises, it is suggested that athletes gain experience by performing 3 to 4 EOL-conditioning sessions prior to utilizing this training method as part of a PAP protocol. Furthermore, the dimensions of common flywheel devices offer useful and practical solutions to induce PAP effects outside normal training environments and in competitions. Although mobilizing barbells and weight plates can be challenging, such challenges are minimized with flywheel devices, making them a logistically excellent PAP-inducing tool for such situations.

Limitations and Future Directions

A few limitations emerged from the existing literature, which should be acknowledged and discussed in view of future research directions. In particular, none of the studies reported in this review have enrolled professional senior team-sport or female athletes, which causes uncertainty about the beneficial application of EOL-based PAP protocols to enhance athletic performances in these populations. The potentiation responses induced by traditional PAP protocols are clearly mediated by the participants' training background, strength, and power capabilities. Conversely, there is no evidence about the concurrent role of individual subjects' physical characteristics or any of the EOL-related performances (eg, maximal and average force and power outputs) on the potentiating effects on subsequent athletic performance. These aspects should be addressed and investigated through dedicated research designs. In addition, EOL requires large force and power output during execution; thus, a relatively lower volumes (eg, 3 sets) of the PAP conditioning activity seem to be a viable approach. This could also reduce the transitory muscular fatigue and thereby allowing potentiation effects to be realized earlier (eg, <3 vs >6 min) and to a greater extent (eg, moderate vs small effects) compared with higher conditioning volumes (>3 sets), but future research is needed to clarify this statement. The relatively greater mechanical demands and the specificity of the EOL exercises also highlight the importance of longer familiarization periods compared with traditional resistance exercises before their implementation as PAP protocols.[42] Indeed, it may be the case that the PAP effects will increase with experience gained in performing EOL exercises. EOL exercise is commonly performed through a variety of brands and flywheel models having different designs, inertial mechanisms, manufacturing materials, and friction coefficients. This is the main reason behind the lack of gold standard valid and reliable procedures that objectively determine the magnitude of inertial loads and associated intensities.

Future studies are warranted to determine which EOL exercise modalities among intensity (inertias), volume (sets and repetitions), rest interval, and exercise type optimally induce the PAP phenomenon and enhance athletic performances. For example, using metrics such as mean velocity, could provide objective feedback on both concentric and eccentric outputs during the flywheel exercise for more precise intensity prescription and monitoring. This could also enable relative intensities to be quantified between athletes or within athlete at a given inertial load. Another research direction worth perusing is the usefulness of self-regulating the output produced with flywheel devices to better manage accumulating fatigue and, thus, to optimize the PAP response. Furthermore, in all studies, the same PAP-inducing exercise (half squats and lunges) was utilized. It would thus be of value to study other exercises (eg, horizontal dominant) as well in future studies. Finally, only 2 studies compared EOL to traditional gravitational resistance protocols as the PAP-inducing modality. Given the extensive knowledge of gravitational resistance exercise on PAP, a comparison of EOL to such exercise would shed further light on the overall usefulness of EOL as a tool to induce PAP.

Conclusions

EOL exercises performed through inertial flywheel devices can be used as an alternative PAP method to acutely potentiate athletic performance. This review describes the theoretical rationale of using EOL exercises to induce potentiation effects and the underpinning mechanisms favoring enhanced performance. The contemporary literature provides preliminary methodological guidelines for coaches and practitioners intending to design PAP protocols by using EOL exercises. Future research is required to clarify the acute effects induced by EOL exercises in order to optimize their use as a PAP methodology in sport.

References

1. Tillin NA, Bishop D. Factors modulating post-activation potentiation and its effect on performance of subsequent explosive activities. *Sports Med*. 2009;39(2):147–166. PubMed ID: 19203135 doi:10.2165/00007256-200939020-00004
2. Boullosa D, Del Rosso S, Behm DG, Foster C. Post-activation potentiation (PAP) in endurance sports: a review. *Eur J Sport Sci*. 2018;18(5):595–610. PubMed ID: 29490594 doi:10.1080/17461391.2018.1438519
3. Seitz LB, Haff GG. Factors modulating post-activation potentiation of jump, sprint, throw, and upper-body ballistic performances: a systematic review with meta-analysis. *Sports Med*. 2016;46(2):231–240. PubMed ID: 26508319 doi:10.1007/s40279-015-0415-7
4. MacIntosh BR, Grange RW, Cory CR, Houston ME. Myosin light chain phosphorylation during staircase in fatigued skeletal muscle. *Pflugers Arch*. 1993;425(1–2):9–15. doi:10.1007/BF00374497
5. MacIntosh BR. Cellular and whole muscle studies of activity dependent potentiation. *Adv Exp Med Biol*. 2010;682:315–342. PubMed ID: 20824534 doi:10.1007/978-1-4419-6366-6_18
6. Beato M, Stiff A, Coratella G. Effects of postactivation potentiation after an eccentric overload bout on countermovement jump and lower-limb muscle strength [published online ahead of print January 4, 2019]. *J Strength Cond Res*. doi:10.1519/JSC.0000000000003005
7. Baudry S, Duchateau J. Postactivation potentiation in a human muscle: effect on the rate of torque development of tetanic and voluntary isometric contractions. *J Appl Physiol*. 2007;102(4):1394–1401. PubMed ID: 17204572 doi:10.1152/japplphysiol.01254.2006
8. Sweeney HL, Bowman BF, Stull JT. Myosin light chain phosphorylation in vertebrate striated muscle: regulation and function. *Am J Physiol*. 1993;264(5, pt 1):C1085–C1095. PubMed ID: 8388631 doi:10.1152/ajpcell.1993.264.5.C1085
9. de Hoyo M, de la Torre A, Pradas F, et al. Effects of eccentric overload bout on change of direction and performance in soccer players. *Int J Sports Med*. 2014;36(04):308–314. doi:10.1055/s-0034-1395521
10. Abbate F, Sargeant AJ, Verdijk PWL, de Haan A. Effects of high-frequency initial pulses and posttetanic potentiation on power output of skeletal muscle. *J Appl Physiol*. 2000;88(1):35–40. PubMed ID: 10642359 doi:10.1152/jappl.2000.88.1.35
11. Vandenboom R, Grange RW, Houston ME. Threshold for force potentiation associated with skeletal myosin phosphorylation. *Am J Physiol Physiol*. 1993;265(6):C1456–C1462. doi:10.1152/ajpcell.1993.265.6.C1456
12. Bauer P, Sansone P, Mitter B, Makivic B, Seitz LB, Tschan H. Acute effects of back squats on countermovement jump performance across multiple sets of a contrast training protocol in resistance-trained men. *J Strength Cond Res*. 2019;33(4):995–1000. PubMed ID: 29309389 doi:10.1519/JSC.0000000000002422
13. Wallace BJ, Shapiro R, Wallace KL, Abel MG, Symons TB. Muscular and neural contributions to postactivation potentiation. *J Strength Cond Res*. 2019;33(3):615–625. PubMed ID: 30589723 doi:10.1519/JSC.0000000000003011
14. Zucker RS, Regehr WG. Short-term synaptic plasticity. *Annu Rev Physiol*. 2002;64(1):355–405. http://www.scholarpedia.org/article/Short-term_synaptic_plasticity
15. Suchomel TJ, Nimphius S, Stone MH. The importance of muscular strength in athletic performance. *Sports Med*. 2016;46(10):1419–1449. PubMed ID: 26838985 doi:10.1007/s40279-016-0486-0

16. Skurvydas A, Jurgelaitiene G, Kamandulis S, et al. What are the best isometric exercises of muscle potentiation? *Eur J Appl Physiol*. 2019;119(4):1029–1039. PubMed ID: 30734104 doi:10.1007/s00421-019-04092-y
17. Guellich A, Güllich A, Sehmidtbleicher D. Potentiation of explosive force. *IAAF*. 1996;4(October):67–80.
18. Rixon KP, Lamont HS, Bemben MG. Influence of type of muscle contraction, gender, and lifting experience on postactivation potentiation performance. *J Strength Cond Res*. 2007;21(2):500–505. PubMed ID: 17530946 doi:10.1519/R-18855.1
19. Behm DG, Button DC, Barbour G, Butt JC, Young WB. Conflicting effects of fatigue and potentiation on voluntary force. *J Strength Cond Res*. 2004;18(2):365–372. PubMed ID: 15141999 doi:10.1519/R-12982.1
20. Wilson JM, Duncan NM, Marin PJ, et al. Meta-analysis of postactivation potentiation and power: effects of conditioning activity, volume, gender, rest periods, and training status. *J Strength Cond Res*. 2013;27(3):854–859. PubMed ID: 22580978 doi:10.1519/JSC.0b013e31825c2bdb
21. Maloney SJ, Turner AN, Fletcher IM. Ballistic exercise as a preactivation stimulus: a review of the literature and practical applications. *Sports Med*. 2014;44(10):1347–1359. doi:10.1007/s40279-014-0214-6
22. Dello Iacono A, Beato M, Halperin I. The effects of cluster-set and traditional-set post activation potentiation protocols on vertical jump performance [published online ahead of print October 15, 2019]. *Int J Sports Physiol Perform*. doi:10.1123/ijspp.2019-0186
23. Hamada T, Sale DG, MacDougall JD, Tarnopolsky MA. Postactivation potentiation, fiber type, and twitch contraction time in human knee extensor muscles. *J Appl Physiol*. 2000;88(6):2131–2137. PubMed ID: 10846027 doi:10.1152/jappl.2000.88.6.2131
24. Dobbs WC, Tolusso D V, Fedewa M V, Esco MR. Effect of postactivation potentiation on explosive vertical jump: a systematic review and meta-analysis. *J Strength Cond Res*. 2019;33(7):2009–2018. PubMed ID: 30138241 doi:10.1519/JSC.0000000000002750
25. Docherty D, Hodgson MJ. The application of postactivation potentiation to elite sport. *Int J Sports Physiol Perform*. 2007;2(4):439–444. PubMed ID: 19171961 doi:10.1123/ijspp.2.4.439
26. Dello Iacono A, Martone D, Padulo J. Acute effects of drop-jump protocols on explosive performances of elite handball players. *J Strength Cond Res*. 2016;30(11):3122–3133. PubMed ID: 26958786 doi:10.1519/JSC.0000000000001393
27. Dello Iacono A, Seitz LB. Hip thrust-based PAP effects on sprint performance of soccer players: heavy-loaded versus optimum-power development protocols. *J Sports Sci*. 2018;36(20):2375–2382. PubMed ID: 29595081 doi:10.1080/02640414.2018.1458400
28. Dello Iacono A, Padulo J, Seitz LD. Loaded hip thrust-based PAP protocol effects on acceleration and sprint performance of handball players. *J Sports Sci*. 2018;36(11):1269–1276. PubMed ID: 28873044 doi:10.1080/02640414.2017.1374657
29. Hansen TE, Lindhard J. On the maximum work of human muscles especially the flexors of the elbow. *J Physiol*. 1923;57(5):287–300. PubMed ID: 16993572 doi:10.1113/jphysiol.1923.sp002066
30. Berg HE, Tesch A. A gravity-independent ergometer to be used for resistance training in space. *Aviat Space Environ Med*. 1994;65(8):752–756. PubMed ID: 7980338
31. Dudley GA, Tesch PA, Miller BJ, Buchanan P. Importance of eccentric actions in performance adaptations to resistance training. *Aviat Space Environ Med*. 1991;62(6):543–550. PubMed ID: 1859341
32. Vicens-Bordas J, Esteve E, Fort-Vanmeerhaeghe A, Bandholm T, Thorborg K. Skeletal muscle functional and structural adaptations after eccentric overload flywheel resistance training: a systematic review and meta-analysis. *J Sci Med Sport*. 2018;21(1):2–3. PubMed ID: 28965851 doi:10.1016/j.jsams.2017.09.001
33. Colliander EB, Tesch PA. Effects of eccentric and concentric muscle actions in resistance training. *Acta Physiol Scand*. 1990;140(1):31–39. PubMed ID: 2275403 doi:10.1111/j.1748-1716.1990.tb08973.x
34. Beato M, De Keijzer KL, Leskauskas Z, Allen WJ, Dello Iacono A, McErlain-Naylor SA. Effect of postactivation potentiation after medium vs. high inertia eccentric overload exercise on standing long jump, countermovement jump, and change of direction performance [published online ahead of print June 19, 2019]. *J Strength Cond Res*. doi:10.1519/JSC.0000000000003214
35. Núñez FJ, Suarez-Arrones LJ, Cater P, Mendez-Villanueva A. The high-pull exercise: a comparison between a VersaPulley flywheel device and the free weight. *Int J Sports Physiol Perform*. 2017;12(4):527–532. PubMed ID: 27705034 doi:10.1123/ijspp.2016-0059
36. Piqueras-Sanchiz F, Martín-Rodríguez S, Martínez-Aranda LM, et al. Effects of moderate vs. high iso-inertial loads on power, velocity, work and hamstring contractile function after flywheel resistance exercise. *PLoS One*. 2019;14(2):e0211700. PubMed ID: 30730959 doi:10.1371/journal.pone.0211700
37. Gonzalo-Skok O, Tous-Fajardo J, Valero-Campo C, et al. Eccentric-overload training in team-sport functional performance: constant bilateral vertical versus variable unilateral multidirectional movements. *Int J Sports Physiol Perform*. 2017;12(7):951–958. PubMed ID: 27967273 doi:10.1123/ijspp.2016-0251
38. Tous-Fajardo J, Maldonado RA, Quintana JM, Pozzo M, Tesch PA. The flywheel leg-curl machine: offering eccentric overload for hamstring development. *Int J Sports Physiol Perform*. 2006;1(3):293–298. PubMed ID: 19116442 doi:10.1123/ijspp.2013-0547
39. Tous-Fajardo J, Gonzalo-Skok O, Arjol-Serrano JL, Tesch P. Enhancing change-of-direction speed in soccer players by functional inertial eccentric overload and vibration training. *Int J Sports Physiol Perform*. 2016;11(1):66–73. PubMed ID: 25942419 doi:101123/ijspp.2015-0010
40. Norrbrand L, Fluckey JD, Pozzo M, Tesch PA. Resistance training using eccentric overload induces early adaptations in skeletal muscle size. *Eur J Appl Physiol*. 2008;102(3):271–281. PubMed ID: 17926060 doi:10.1007/s00421-007-0583-8
41. Vicens-Bordas J, Esteve E, Fort-Vanmeerhaeghe A, Bandholm T, Thorborg K. Is inertial flywheel resistance training superior to gravity-dependent resistance training in improving muscle strength? A systematic review with meta-analyses. *J Sci Med Sport*. 2017;21(1):75–83. PubMed ID: 29107539 doi:10.1016/j.jsams.2017.10.006
42. Sabido R, Hernández-Davó JL, Pereyra-Gerber GT. Influence of different inertial loads on basic training variables during the flywheel squat exercise. *Int J Sports Physiol Perform*. 2018;13(4):482–489. PubMed ID: 28872379 doi:10.1123/ijspp.2017-0282
43. Vázquez-Guerrero J, Moras G, Baeza J, Rodríguez-Jiménez S. Force outputs during squats performed using a rotational inertia device under stable versus unstable conditions with different loads. *PLoS One*. 2016;11(4):e0154346. doi:10.1371/journal.pone.0154346
44. Douglas J, Pearson S, Ross A, McGuigan M. Effects of accentuated eccentric loading on muscle properties, strength, power, and speed in resistance-trained rugby players. *J Strength Cond Res*. 2018;32(10):2750–2761. PubMed ID: 30113915 doi:10.1519/JSC.0000000000002772
45. Nardone A, Romanò C, Schieppati M. Selective recruitment of high-threshold human motor units during voluntary isotonic lengthening of active muscles. *J Physiol*. 1989;409:451–471. PubMed ID: 2585297 doi:10.1113/jphysiol.1989.sp017507

46. Coratella G, Bellin G, Beato M, Schena F. Fatigue affects peak joint torque angle in hamstrings but not in quadriceps. *J Sports Sci*. 2015;33(12):1276–1282. PubMed ID: 25517892 doi:10.1080/02640414.2014.986185
47. Higbie EJ, Cureton KJ, Warren GL, Prior BM. Effects of concentric and eccentric training on muscle strength, cross-sectional area, and neural activation. *J Appl Physiol*. 1996;81(5):2173–2181. PubMed ID: 8941543 doi:10.1152/jappl.1996.81.5.2173
48. Fahs CA, Rossow LM, Zourdos MC. Analysis of factors related to back squat concentric velocity. *J Strength Cond Res*. 2018;32(9):2435–2441. PubMed ID: 30137028 doi:10.1519/JSC.0000000000002295
49. Fang Y, Siemionow V, Sahgal V, Xiong F, Yue GH. Greater movement-related cortical potential during human eccentric versus concentric muscle contractions. *J Neurophysiol*. 2001;86(4):1764–1772. PubMed ID: 11600637 doi:10.1152/jn.2001.86.4.1764
50. Norrbrand L, Pozzo M, Tesch PA. Flywheel resistance training calls for greater eccentric muscle activation than weight training. *Eur J Appl Physiol*. 2010;110(5):997–1005. PubMed ID: 20676897 doi:10.1007/s00421-010-1575-7
51. Cormie P, McGuigan MR, Newton RU. Developing maximal neuromuscular power. *Sports Med*. 2011;41(2):125–146. doi:10.2165/11538500-000000000-00000
52. Maroto-Izquierdo S, García-López D, Fernandez-Gonzalo R, Moreira OC, González-Gallego J, de Paz JA. Skeletal muscle functional and structural adaptations after eccentric overload flywheel resistance training: a systematic review and meta-analysis. *J Sci Med Sport*. 2017;20(10):943–951. PubMed ID: 28385560 doi:10.1016/j.jsams.2017.03.004
53. Markovic G, Mikulic P. Neuro-musculoskeletal and performance adaptations to lower-extremity plyometric training. *Sports Med*. 2010;40(10):859–895. doi:10.2165/11318370-000000000-00000
54. Lakens D. Calculating and reporting effect sizes to facilitate cumulative science: a practical primer for *t*-tests and ANOVAs. *Front Psychol*. 2013;4(November):1–12. doi:10.3389/fpsyg.2013.00863
55. Cohen J. *Statistical Power Analysis for the Behavioral Sciences*. NewYork, NY: Routledge Academic; 1988.
56. Cuenca-Fernández F, López-Contreras G, Arellano R. Effect on swimming start performance of two types of activation protocols: lunge and YoYo squat. *J Strength Cond Res*. 2015;29(3):647–655. doi:10.1519/JSC.0000000000000696
57. Cuenca-Fernández F, Ruiz-Teba A, López-Contreras G, Arellano R. Effects of 2 types of activation protocols based on postactivation potentiation on 50-m freestyle performance [published online ahead of print June 14, 2018]. *J Strength Cond Res*. doi:10.1519/JSC.0000000000002698
58. Cuenca-Fernández F, López-Contreras G, Mourão L, et al. Eccentric flywheel post-activation potentiation influences swimming start performance kinetics. *J Sports Sci*. 2019;37(4):443–451. doi:10.1080/02640414.2018.1505183
59. Timon R, Allemano S, Camacho-Cardeñosa M, Camacho-Cardeñosa A, Martinez-Guardado I, Olcina G. Post-activation potentiation on squat jump following two different protocols: traditional vs. inertial flywheel. *J Hum Kinet*. 2019;69(1):271–281. doi:10.2478/hukin-2019-0017
60. Hägglund M, Waldén M, Ekstrand J. Risk factors for lower extremity muscle injury in professional soccer. *Am J Sports Med*. 2013;41(2):327–335. doi:10.1177/0363546512470634
61. Gouvêa AL, Fernandes IA, César EP, Silva WAB, Gomes PSC. The effects of rest intervals on jumping performance: a meta-analysis on post-activation potentiation studies. *J Sports Sci*. 2013;31(5):459–467. doi:10.1080/02640414.2012.738924