EFFECTS OF POSTACTIVATION POTENTIATION AFTER AN ECCENTRIC OVERLOAD BOUT ON COUNTERMOVEMENT JUMP AND LOWER-LIMB MUSCLE STRENGTH

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ABSTRACT

Beato, M, Stiff, A, and Coratella, G. Effects of postactivation potentiation after an eccentric overload bout on countermovement jump and lower-limb muscle strength. *J Strength Cond Res* XX(X): 000–000, 2018—This study aimed to evaluate the postactivation potentiation (PAP) effects of an eccentric overload (EOL) exercise on countermovement jump (CMJ) performance and isokinetic lower-limb muscle strength. Eighteen active men (mean ± *SD*, age 20.2 ± 1.4 years, body mass 71.6 ± 8 kg, and height 178 ± 7 cm) were involved in a randomized, crossover study. The participants performed 3 sets per 6 repetitions of EOL half squats at maximal power using a flywheel ergometer. Postactivation potentiation using an EOL exercise was compared with a control condition (10-minute cycling at 1 $W \cdot kg^{-1}$). Countermovement jump height, peak power, impulse, and force were recorded at 15 seconds, 1, 3, 5, 7, and 9 minutes after an EOL exercise or control. Furthermore, quadriceps and hamstrings isokinetic strength were performed. Postactivation potentiation vs. control reported a meaningful difference for CMJ height after 3 minutes (effect size [ES] = 0.68, $p = 0.002$), 5 minutes (ES = 0.58, $p = 0.008$), 7 minutes (ES = 0.57, $p = 0.022$), and 9 minutes (ES = 0.61, $p = 0.002$), peak power after 1 minute (ES = 0.22, $p = 0.040$), 3 minutes (ES = 0.44, $p = 0.009$), 5 minutes (ES = 0.40, $p = 0.002$), 7 minutes (ES = 0.29, $p = 0.011$), and 9 minutes (ES = 0.30, $p = 0.008$), as well as quadriceps concentric, hamstrings concentric, and hamstrings eccentric peak torque (ES = 0.13, $p = 0.001$, ES = 0.24, $p = 0.003$, and ES = 0.22, $p = 003$, respectively) after 3–9 minutes of rest. In conclusion, the present outcomes highlight that PAP using an EOL bout improves height, peak power, impulse, and peak force during CMJ, as well as quadriceps and hamstrings isokinetic strength in male athletes. Moreover, the optimal time window for the PAP was found from 3 to 9 minutes.

KEY WORDS warm-up, power, flywheel, isokinetic, quadriceps, hamstrings

INTRODUCTION

Postactivation potentiation (PAP) refers to a phenomenon associated with an acute improvement in muscular performance after a warm-up strategy or a strength exercise protocol, i.e., a preload stimulus (14,16). Although its underlying mechanisms are still unknown, previous studies reported that neuromuscular, mechanical, and biochemical changes could induce these temporary improvements in performance (6,21,27). The most accredited physiological explanation is associated with the phosphorylation of the myosin regulatory light chains during a muscle contraction, which leads to a greater rate of cross-bridge attachment (3,16). This is due to an increased sensitivity of the contractile proteins to calcium (Ca^{2+}), which is released from the sarcoplasmic reticulum and the subsequent muscle response (e.g., twitch force and rate of force development) results increased (1–3). Other evidence has reported that greater motor unit recruitment (higher postsynaptic potentials and H-wave) could also affect the PAP (1). These factors play a critical role in the acute improvements of mechanical power and consequent athletic performance after a preload stimulus (13).

Postactivation potentiation protocols have been used to acutely improve performance in competitions and training sessions (25) as a warm-up to increase the voluntary explosive actions (18). Such acute improvements in performance were shown to persist up to 10 minutes (1,3). In the literature, several methods to induce PAP in athletes and untrained people are described, such as dynamic or isometric strength exercise, cycling, and sport-specific warm-up (19,27). Previous evidence reported that dynamic-constant external load exercise protocols increased the muscular

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power after a bout of heavy or by light resistance exercise (1). In addition, maximal isometric voluntary contractions have induced a PAP and subsequent improvements in the rate of force development (2). It was reported that heavy resistance exercise improved repeated sprint ability in adult handball players (25) and youth athletes (19). Similar improvements have been reported in linear sprint in adult soccer players (21) and women college sprinters (100 m) (18). Parallel back squat (1 × 5 repetition maximum [RM]) showed to potentiate performance in sprints and jumps in active men (5,28). Back squat exercise using heavy load (4 × 90% of 1RM) and moderate load (6 × 60% of 1RM) reported PAP to countermovement jump (CMJ) performance in resistance-trained male subjects (3).

Eccentric overload (EOL) exercise is a methodology used to improve sports performance, and it is commonly generated by flywheel devices (16,29). During an EOL exercise, the concentric phase is weight-free, and the eccentric phase is enhanced by the inertia accumulated during the concentric phase (12,16). Higher electromyographic activity has been reported during an EOL bout compared with traditional weight exercise (24). Eccentric overload training has shown important practical applications for strength conditioning coaches. For example, it has been reported that EOL elicits improvements in strength and power that play a functional role in most of the required movements in sport (16,20). However, most studies published to date had a focus on chronic adaptations (20,24,30), while only a few have analyzed the acute benefits of PAP after an EOL protocol (13,29). Recent studies have reported that PAP developed by EOL improved jump and 20-m sprint performance in highly training soccer players (16), as well as meaningful improvements in horizontal velocity (5 and 15 m) and angular velocity of knee extension in swimmers (13). Studies on PAP found positive performance improvements after strength exercises (using traditional preload strategies), while others have failed to confirm these results (3,18,21). These inconsistent findings could be ascribed to the several factors that affect the PAP response such as training volume, intensity, rest duration, and time windows after the exercise protocol (1).

Countermovement jump is a method to evaluate lower-limb muscle power, and previous studies have reported the validity of isokinetic tests to evaluate lower-limb muscle strength (4,10,32). Particularly, both quadriceps and hamstrings strength are crucial for several sports activities (10), and their balance may help to prevent hamstring injury (11). To date, there is not any evidence about the acute effects of EOL bout on CMJ performance and lower-limb muscle strength. Moreover, no data are available regarding the PAP time-course as well as the magnitude of the effects using a flywheel device. This information could be critical for the development of strength training strategies and power optimization before a training session or a competition. Therefore, the aim of this study was to evaluate the effects of PAP of an EOL exercise (half squat) vs. a traditional warm-up on CMJ performance (jump height, peak power, impulse, and force) and quadriceps and hamstrings isokinetic strength in male athletes.

METHODS

Experimental Approach to the Problem

The acute effects induced by EOL (experimental condition) vs. a traditional warm-up (control condition) on CMJ

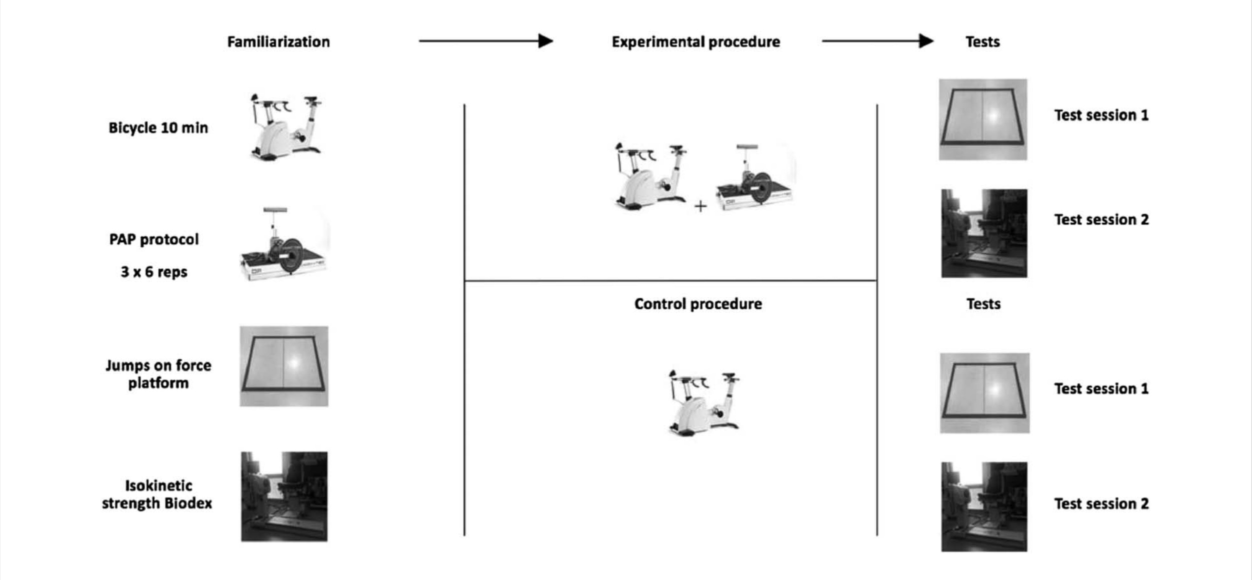

Figure 1. Experimental and control procedure.

TABLE 1. Summary of control and PAP jump and power data ($n = 18$).*†

Variable	Control, mean ± *SD*s	PAP, mean ± *SD*s	Delta difference (90% CI)	Effect size (90% CI)	*P* level	Effect size assessment
Jumps height						
Jump 15 s (cm)	32.9 ± 6.3	32.1 ± 7.0	−0.8 (−1.7 to 0.1)	−0.12 (−0.24 to −0.02)	0.096	Trivial
Jump 1 min (cm)	32.6 ± 5.7	35.3 ± 8.5	2.6 (0.9 to 4.6)	0.47 (0.08 to 0.86)	0.053	Small
Jump 3 min (cm)	33.4 ± 6.3	37.7 ± 8.7	4.2 (2.5 to 6.1)	0.68 (0.35 to 1)	0.002	Moderate
Jump 5 min (cm)	32.3 ± 6.2	36.9 ± 7.8	4.5 (2.1 to 5.6)	0.58 (0.24 to 0.92)	0.008	Small
Jump 7 min (cm)	32.1 ± 6.2	36.1 ± 8.2	3.9 (2.4 to 5.6)	0.57 (0.18 to 0.96)	0.022	Small
Jump 9 min (cm)	32.6 ± 6.3	37.2 ± 8.4	5.1 (3.9 to 6.5)	0.61 (0.32 to 0.9)	0.002	Moderate
Peak power						
Power 15 s (W)	3,137 ± 646	3,102 ± 575	−37 (−141 to 91)	0.05 (−0.10 to 0.20)	0.577	Trivial
Power 1 min (W)	3,184 ± 654	3,324 ± 623	139 (48 to 239)	0.22 (0.05 to 0.39)	0.040	Small
Power 3 min (W)	3,108 ± 653	3,297 ± 595	189 (92 to 293)	0.44 (0.18 to 0.7)	0.009	Small
Power 5 min (W)	3,018 ± 514	3,277 ± 566	253 (164 to 334)	0.40 (0.21 to 0.59)	0.002	Small
Power 7 min (W)	3,037 ± 557	3,208 ± 597	171 (72 to 274)	0.29 (0.11 to 0.47)	0.011	Small
Power 9 min (W)	3,050 ± 554	3,221 ± 587	172 (86 to 270)	0.30 (0.13 to 0.47)	0.008	Small

*PAP = postactivation potentiation; CI = confidence interval.
†Data are presented in mean ± *SD*.

performance and isokinetic peak torque were investigated in the present randomized, crossover study design. Each participant attended the laboratory on 5 separate occasions. The first one served to familiarize participants with the EOL exercise, the CMJ, and the isokinetic testing procedures. Within the remaining 4 sessions, the participants performed 1 of the 4 testing protocols in a randomized order: CMJ tests after a standardized warm-up (control), isokinetic assessments after a standardized warm-up (control), CMJ tests after a standardized warm-up, and EOL exercise (experimental condition) and isokinetic assessments after a standardized warm-up and EOL exercise (experimental condition).

Subjects

Eighteen active men were enrolled in this study (mean ± *SD*; age 20.2 ± 1.4 years, range 18-24 years old, body mass 71.6 ± 8 kg, and height 178 ± 7 cm). Inclusive criteria for participation were the absence of any injury or illness (PAR-Q), a regular training activity with a minimum of 3 training sessions per week and a regular participation to competitions (athletes of different sport background were enrolled such as soccer, American football, and rugby). All participants were informed about the potential risks and benefits of the current procedures and signed an informed consent form. The Ethics Committee of the School of Science, Technology and Engineering, University of Suffolk (UK), approved this study. All procedures were conducted according to the Declaration of Helsinki for studies involving human subjects. To calculate the sample size, statistical software (GPower, Dusseldorf, Germany) was used. Given the study 2-way analysis of variance (ANOVA) (2 group and 6 repeated measures), a medium overall effect size (ES) $f = 0.25$, an α-error ≤ 0.05, and a desired power (1-ß error) = 0.8, the total sample size resulted in 15 participants. To prevent the effects of any possible dropout on the statistical power, 18 participants were included.

Procedures

Body mass and height were recorded by Stadiometer (Seca 286dp; Seca, Hamburg, Germany). A standardized warm-up including 10 minutes of cycling at a constant power (1 W per kg of body mass) on an ergometer (workload range of 8–2,500 W, Sport Excalibur lode, Groningen, the Netherlands)

TABLE 2. Summary of control and PAP impulse and force data ($n = 18$).*†

Variable	Control, mean ± *SD*s	PAP, mean ± *SD*s	Delta difference (90% CI)	Effect size (90% CI)	*p*-level	Effect size assessment
Jump impulse						
Impulse 15 s (N·m)	177.5 ± 33.4	173.9 ± 39.5	−3.6 (−9.3 to 2.6)	−0.10 (−0.25 to 0.05)	0.263	Trivial
Impulse 1 min (N·m)	178.3 ± 39.3	182.9 ± 35.3	4.6 (0.18 to 9.1)	0.13 (−0.01 to 0.26)	0.105	Trivial
Impulse 3 min (N·m)	178.5 ± 34.4	182.1 ± 36.8	3.6 (−2.4 to 9.6)	0.11 (−0.08 to 0.3)	0.330	Trivial
Impulse 5 min (N·m)	176.6 ± 33.7	185.6 ± 37.7	9.0 (5.2 to 13.4)	0.26 (0.08 to 0.44)	0.021	Small
Impulse 7 min (N·m)	175.3 ± 32.4	184.9 ± 38.9	9.6 (4.3 to 15.3)	0.27 (0.09 to 0.45)	0.016	Small
Impulse 9 min (N·m)	175.5 ± 33.4	184.8 ± 38.2	9.3 (4.4, 14.7)	0.27 (0.07 to 0.47)	0.029	Small
Jump force						
Force 15 s (N)	1,586 ± 355	1,540 ± 386	−46 (−77 to −24)	−0.12 (−0.23 to −0.01)	0.066	Trivial
Force 1 min (N)	1,579 ± 370	1,605 ± 393	25 (1 to 53)	0.07 (−0.01 to 0.15)	0.130	Trivial
Force 3 min (N)	1,566 ± 348	1,601 ± 390	34 (6 to 60)	0.09 (0.01 to 0.18)	0.088	Trivial
Force 5 min (N)	1,530 ± 300	1,615 ± 376	85 (41 to 130)	0.25 (0.08 to 0.42)	0.021	Small
Force 7 min (N)	1,518 ± 366	1,604 ± 411	85 (46 to 129)	0.23 (0.11 to 0.35)	0.005	Small
Force 9 min (N)	1,532 ± 346	1,597 ± 413	64 (28 to 104)	0.18 (0.06 to 0.31)	0.026	Trivial

*PAP = postactivation potentiation; CI = confidence interval.
†Data are presented in mean ± *SD*.

and dynamic mobilization was performed in both the control and experimental conditions (3).

Two sessions were performed as control where participants performed CMJ tests (control session 1) and an isokinetic test (control session 2) after the conclusion of the warm-up without any additional strength exercise. The same warm-up previously described (10 minutes of cycling at a constant power) was used on each occasion. Countermovement jump tests were performed immediately after the end of the warm-up at 15 seconds, 1, 3, 5, 7, and 9 minutes. This jump series were conducted during each of the subsequent conditions (control and experimental). Isokinetic test was performed between 3 and 9 minutes after the end of the warm-up. This time window has been used to optimize the effects of PAP as previously reported (2,3,27).

The experimental condition used the same procedure described for the control but involving also an EOL exercise after the warm-up. Therefore, the CMJ protocol was performed immediately after EOL exercise (experimental session 1) and the isokinetic evaluations (experimental session 2) (Figure 1).

Countermovement Jump. Countermovement jump was assessed using a force platform (Kistler, Winterthur, Switzerland) using a sampling rate of 1,000 Hz (22). The participants were instructed to stand, lower themselves to a self-selected knee flexion and immediately jump and were encouraged to maximally perform each jump. The participants were instructed to avoid any knee flexion before the landing and to keep their hands on their hips to prevent the influence of arm movements on vertical jump performance, under the supervision of an experienced operator. The following variables were inserted into the data analysis: jump height (cm), peak power (W), impulse ($N\cdot kg^{-1}$), and peak jumping force (N). *Excellent* test-retest reliability was found for each parameter: $\alpha = 0.910$, $\alpha = 0.922$, $\alpha = 0.918$, and $\alpha = 0.901$. Jump height was defined as the vertical displacement achieved by the center of mass from take-off to the vertex of the flight trajectory using time in the air (TIA):

$$\text{TIA jump height} = 1/2\ g\ (t/2)^2,$$

where $g = 9.81\ m\cdot s^{-2}$ and t = time in air (23).

Isokinetic Testing Assessment. An isokinetic dynamometer (Biodex Medical Systems, Shirley, NY, USA) was used to measure the quadriceps and hamstrings strength. The procedures followed previous recommendations (9,17): Briefly, the device was calibrated according to the manufacturer's procedures, and the center of rotation was aligned with the tested knee. The participants were seated on the dynamometer chair, with their trunks slightly reclined

Table 3. Summary of control and PAP Isokinetic data ($n = 18$).*†

Variable	Control, mean ± *SD*s	PAP, mean ± *SD*s	Delta difference, (90% CI)	Effect size, (90% CI)	p-level	Effect size assessment
Peak torque ($60^\circ\cdot s^{-1}$)						
Quad conc ($Nm\cdot kg^{-1}$)	205 ± 53	212 ± 53	7.7 (4.6 to 10.9)	0.13 (0.07 to 0.19)	0.001	Trivial
Ham conc ($Nm\cdot kg^{-1}$)	124 ± 35	133 ± 37	9.6 (4.8 to 14.4)	0.24 (0.12 to 0.36)	0.003	Small
Ham ecc ($Nm\cdot kg^{-1}$)	147 ± 55	159 ± 52	12.1 (6.1 to 18.1)	0.22 (0.11 to 0.33)	0.003	Small
Ratio ($60^\circ\cdot s^{-1}$)						
Conventional ratio	0.60 ± 0.05	0.63 ± 0.09	0.03 (0.01 to 0.05)	0.6 (0.03 to 1.2)	0.083	Moderate
Functional ratio	0.71 ± 0.14	0.78 ± 0.14	0.07 (0.03 to 0.09)	0.21 (0.12 to 0.3)	0.001	Small

*PAP = postactivation potentiation; Quad = quadriceps; Ham = hamstring; Conc = concentric; Ecc = eccentric; CI = confidence interval.

†Data are presented in mean ± *SD*.

backwards and a hip angle of 95°. Two seatbelts secured the trunk, and one strap secured the tested limb, while the untested limb was secured by an additional lever. The quadriceps peak torque was measured in concentric ($60^\circ\cdot s^{-1}$), and the hamstrings peak torque was measured in concentric ($60^\circ\cdot s^{-1}$) and eccentric ($-60^\circ\cdot s^{-1}$) modality. Each testing modality consisted of 3 maximal trials and was separated by 2 minutes of passive recovery. Strongly standardized encouragements were provided to the participants to maximally perform each trial (11,17). The peak torque was then calculated and inserted into the data analysis. Finally, the hamstrings-to-quadriceps strength ratio, defined as the ratio between eccentric hamstrings-to-concentric quadriceps peak torque (i.e., conventional H_{conc}:Q_{conc} ratio and functional H_{ecc}:Q_{conc} ratio), was also calculated (11,26). The dominant limb, defined as the preferred limb used to kick the ball, was tested (2,3). *Excellent* test-retest reliability was found for all the isokinetic measurements ($\alpha = 0.900$–0.944).

Intervention. Eccentric overload was performed by a half squat exercise using a flywheel ergometer (D11 full; Desmotec, Biella, Italy). The PAP protocol consisted of 3 sets × 6 repetitions of half squats at maximal power, interspersed by 2 minutes of passive recovery. Each movement was evaluated by an operator who offered a feedback to the athletes during the EOL exercise. The following combined load was used for each participant: one large disk (diameter = 285 mm, mass = 1.9 kg, and inertia = 0.02 $kg\cdot m^{-2}$) and one medium disk (diameter = 240 mm, mass = 1.1 kg, and inertia = 0.008 $kg\cdot m^{-2}$). The inertia of the machine (D11) was estimated as 0.0011 $kg\cdot m^{-2}$. The participants were instructed to perform the concentric phase as fast as possible and to control the braking phase until the knees where flexed up to approximately 90°. An investigator offered a technique feedback for each repetition. The participants received strong standardized encouragements to maximally perform each repetition.

Statistical Analyses

Statistical analyses were performed by SPSS software version 20 for Windows 7, Chicago, USA. Data were presented as mean ± *SD*. The test-retest reliability was measured using an intraclass correlation coefficient (Cronbach-α) and interpreted as follows: $\alpha \geq 0.9$ = *excellent*; $0.9 > \alpha \geq 0.8$ = *good*; $0.8 > \alpha \geq 0.7$ = *acceptable*; $0.7 > \alpha \geq 0.6$ = *questionable*; $0.6 > \alpha \geq 0.5$ = *poor*; and $\alpha < 0.5$ *unacceptable* (10). One-way repeated-measure ANOVA was used to evaluate the effects of condition (control vs. PAP) on CMJ height, peak power, impulse, and force. If a meaningful F value was found, the Bonferroni correction was applied. Paired t-test was performed between control and PAP for the isokinetic parameters. Robust estimates of 90% confidence interval (15) and heteroskedasticity were calculated using bootstrapping technique (randomly 1,000 bootstrap samples). Significance was set at $p \leq 0.05$ and reported to indicate the strength of the evidence. The ES was calculated and interpreted as follows: <0.20: *trivial*, 0.20–0.59: *small*, 0.60–1.19: *moderate*, 1.20–1.99: l*arge*, and ≥ 2.00 *very large* (15).

Results

The between-group analysis reported differences in CMJ height ($F = 20.8$, $p < 0.001$), power ($F = 11.5$, $p = 0.003$), impulse ($F = 6.5$, $p = 0.020$), and force ($F = 10.6$, $p = 0.005$). The post hoc control vs. PAP conditions on jump and power data are reported in Table 1, whereas impulse and force data are reported in Table 2.

The isokinetic analysis reported meaningful variations between the PAP and control conditions for quadriceps concentric peak torque ($t = 4.3$, $p = 0.001$), hamstrings concentric peak torque ($t = 3.5$, $p = 0.003$), hamstrings eccentric peak torque ($t = 3.5$, $p = 0.003$), H_{conc}:Q_{conc} ratio ($t = 1.8$, $p = 0.083$), and H_{ecc}:Q_{conc} ratio ($t = 3.8$, $p = 0.001$). The PAP vs. control isokinetic data are reported in Table 3.

DISCUSSION

In the literature, no evidence of the acute effects of EOL bout on CMJ performance and isokinetic strength exists to date. Moreover, no data are currently available regarding the optimal PAP time windows, as well as the magnitude of the effects after an EOL exercise. To the best of the authors' knowledge, the current study was the first to evaluate such parameters after a squat exercise performed using an EOL. Compared with control, greater CMJ height was observed after 3, 5, 7, and 9 minutes. Similarly, peak power was greater after 1, 3, 5, 7, and 9 minutes. The CMJ impulse increased after 5, 7, and 9 minutes, as well as CMJ force after 5, 7, and 9 minutes. In addition, greater quadriceps concentric peak torque, hamstrings concentric peak torque, eccentric peak torque, and functional H_{ecc}:Q_{conc} ratio were observed but not in conventional H_{conc}:Q_{conc} ratio.

Postactivation potentiation is defined as a transient increase in muscle performance following a preload strategy (6). It was shown that neuromuscular, mechanical, and biochemical mechanisms could be behind these temporary improvements in performance (21). Stiffness is related to the number and the stability of the bonds between actin and myosin filaments. After a preload activity, many of these bonds are broken and the passive stiffness decreases, which can cause an improvement in performance (6). A further explanation reported in literature is related to the myosin regulatory light chain function that renders the actin-myosin interaction more sensitive to calcium and causes conformational changes of the myosin head, which during a muscle contraction leads to a greater rate of cross-bridge attachment (3,8,16). This mechanism is due to an increased sensitivity in the contractile proteins to calcium (Ca^{2+}), which is released from the sarcoplasmic reticulum, and the subsequent muscle repose results improved (1–3,6,7). Such motivations could explain the improvement in muscle power and rate of force development following a preload strategy (6). Moreover, a major recruitment of higher order motor units (higher postsynaptic potentials and H-wave) through a decreased threshold of activation for the fast-twitch motoneurons during both maximal and submaximal exercise seems to increase the PAP (1,8). The current results agree with previously reported literature using an EOL bout, which has found *small* differences vs. control in CMJ height and 20-m sprint time (16). Moreover, the present findings are in line with the higher peak force and speed reported after an EOL protocol compared with a control condition in swimming athletes (13). The differences found here support previous findings where acute positive effects of heavy traditional resistance exercise on performance in horizontal and vertical jump (28) and time on 5- and 10-m sprint were observed in professional athletes (5). Finally, the present results agree with a previous study where a *moderate* increment in vertical ground reaction force and propulsive force and a *small* increment in total impulse were found after an EOL-based warm-up during a change of direction exercise (16). Therefore, based on the current results and previous evidence, an EOL bout is a valid exercise to stimulate PAP and consequently to overstimulate the lower-limb muscle power.

The current study has not observed any PAP vs. control difference in jump height, peak power, impulse, and peak force at 15 seconds, as well as in impulse and peak force at 1 minute. The current findings agree with a previous study that found a decrement in CMJ height immediately after a back squat exercise (3). This supports that PAP could be related to time-dependent factors (13,27). After a conditioning activity (e.g., preload), fatigue is dissipated quicker than PAP, thus potentiation allows for subsequent increments in performance (e.g., power) (1). The acute fatigue after the EOL exercise could have affected the jump kinematic, as previously reported in swimmers (13). Fatigue is more dominant in the early stage of recovery, but it diminishes at a quicker rate than PAP; therefore, the potentiation of performance may be realized during the following recovery period (1). Previous evidence reported that the optimal time to the PAP development is from 3 to 10 minutes after the exercise (3,5). This study supports such data, reporting a *moderate* difference vs. control in CMJ height and a *small* one in peak power after 3 minutes of passive recovery. However, impulse and peak force differed from control mainly after 5 minutes of passive recovery. This would support that an optimal time window to maximize the performance after the PAP exists (28).

This study used an isokinetic device to evaluate the effects of the PAP on the lower-limb muscle strength. This study found a *trivial* meaningful difference in quadriceps concentric and *small* differences in hamstrings concentric and eccentric peak torque vs. control. However, since this is the first study that investigated these specific acute isokinetic strength responses, a direct comparison with previous literature is challenging. The strength difference reported in the current study after an EOL PAP protocol vs. control could be explained considering the high muscle activation (e.g., increased neural drive) and the mechanical stress obtained by EOL exercise (20,24,29). An enhanced neural drive could be related to a superior motor cortex activation compensating for the spinal inhibition during eccentric phase (31). The positive effect of PAP on lower-limb muscle strength could have several practical implications because the lower-limb isokinetic peak torque was found to be correlated with changes of direction, sprinting and jumping abilities in elite soccer players (10).

Interestingly, a *moderate* and a *small* difference in the H_{conc}:Q_{conc} and H_{ecc}:Q_{cocn} ratio respectively was observed vs. control, i.e., the hamstrings concentric and eccentric peak torque improved more than the quadriceps concentric peak torque. This might depend on the greater overload demanded during the eccentric than the concentric phase (20). Indeed, a greater hamstring vs. quadriceps activity was reported during the eccentric vs. concentric phase of a squat exercise (33). Consequently, the enhanced-eccentric phase may have highlighted this specific hamstring vs. quadriceps activity. These findings are particularly interesting because the hamstrings-to-quadriceps strength ratio has been linked to injury risk and sport-specific performance (10,11). Because fatigue was shown to decrease the H_{ecc}:Q_{cocn} ratio (11), the current results may offer a temporary protection for both training sessions and performance, enhancing the strength of the hamstrings (11). However, some negative effects associated with the temporary fatigue after an EOL PAP protocol (1,2), as well as the short-term muscle damage induced by the eccentric exercise should be considered (12).

The current study presents some limitations. First, this study involved active men only. Therefore, wider generalization cannot be inferred and the results could not be extended to other specific populations (e.g., elite female athletes). Second, vertical jump has been estimated using TIA and not calculated by kinematic data. In addition, it was shown that the fitness level may account for the amount of the PAP response. Indeed, a previous study found major benefits in strength-trained vs. recreational active participants (5). Future studies could replicate the current procedures enrolling a different population. Moreover, future studies are necessary to better evaluate the PAP effects on sport-specific performance considering that PAP response presents large variability among subjects, as well as the known responder vs. nonresponder phenomenon (3,5).

In conclusion, this study suggests that an EOL bout increases the jump height, peak power, impulse, and peak force during a CMJ, as well as the quadriceps and hamstrings isokinetic strength in male athletes. Moreover, the optimal time window for the PAP was found here from 3 to 9 minutes, although some increments could be possible after 1 minute of passive recovery.

Practical Applications

The present outcomes could be used by coaches to optimize strength and power development during training sessions (e.g., contrast training) and before the competition where great power and strength are required (3,4,27). During contrast training, a high-intensity exercise (e.g., squat) can be associated with a plyometric or jump activity involving the same muscle groups (27). The rationale of such training is to use the PAP developed during the preload exercise to improve the performance of the movements selected (e.g., jumps and sprints), which incorporated into long-term training programs that could induce superior chronic neuromuscular adaptations (3,5). Moreover, the authors underline the importance to consider the PAP time window reported in this study to optimize contrast training methodologies and acute athletes' performance. Therefore, coaches should consider a rest period of 3 minutes to optimize the contrast training strategies. Indeed, a minimal recovery period after an EOL exercise seems to have a critical importance for jump performance and muscle strength.

References

1. Anthony, N and Bishop, D. Factors modulating post-activation potentiation and its effects on performance. *Sport Med* 39: 147–166, 2009.
2. Baudry, S and Duchateau, J. Postactivation potentiation in a human muscle: Effect on the rate of torque development of tetanic and voluntary isometric contractions. *J Appl Physiol* 102: 1394–1401, 2007.
3. Bauer, P, Sansone, P, Mitter, B, Makivic, B, Seitz, LB, and Tschan, H. Acute effects of back squats on countermovement jump performance across multiple sets of a contrast training protocol in resistance-trained males. *J Strength Cond Res* 1, 2018. Available at: http://insights.ovid.com/crossref?an=00124278-900000000-95563. Epub ahead of print.
4. Beato, M, Bianchi, M, Coratella, G, Merlini, M, and Drust, B. Effects of plyometric and directional training on speed and jump performance in elite youth soccer players. *J Strength Cond Res* 32: 289–296, 2018.
5. Bevan, HR, Cunningham, DJ, Tooley, EP, Owen, NJ, Cook, CJ, and Kilduff, LP. Influence of postactivation potentiation on sprinting performance in professional rugby players. *J Strength Cond Res* 24: 701–705, 2010.
6. Bishop, D. Warm up I: Potential mechanisms and the effects of passive warm up on exercise performance. *Sports Med* 33: 439–454, 2003.
7. Bishop, D. Warm up II: Performance changes following active warm up and how to structure the warm up. *Sports Med* 33: 483–498, 2003.
8. Bogdanis, GC, Tsoukos, A, and Veligekas, P. Improvement of long-jump performance during competition using a plyometric exercise. *Int J Sports Physiol Perform* 12: 235–240, 2017.
9. Coratella, G, Beato, M, Milanese, C, Longo, S, Limonta, E, Rampichini, S, et al. Specific adaptations in performance and muscle architecture after weighted jump-squat vs. body mass squat jump training in recreational soccer players. *J Strength Cond Res* 32: 921–929, 2018.
10. Coratella, G, Beato, M, and Schena, F. Correlation between quadriceps and hamstrings inter-limb strength asymmetry with change of direction and sprint in U21 elite soccer-players. *Hum Mov Sci* 59: 81–87, 2018.
11. Coratella, G, Bellin, G, Beato, M, and Schena, F. Fatigue affects peak joint torque angle in hamstrings but not in quadriceps. *J Sports Sci* 33: 1276–1282, 2015.
12. Coratella, G, Chemello, A, and Schena, F. Muscle damage and repeated bout effect induced by enhanced eccentric squats. *J Sports Med Phys Fitness* 56: 1540–1546, 2016.
13. Cuenca-Fernández, F, López-Contreras, G, and Arellano, R. Effect on swimming start performance of two types of activation protocols: Lunge and YoYo squat. *J Strength Cond Res* 29: 647–655, 2015.
14. Dello Iacono, A, Martone, D, and Padulo, J. Acute effects of drop-jump protocols on explosive performances of elite handball players. *J Strength Cond Res* 30: 3122–3133, 2016.

15. Hopkins, WG, Marshall, SW, Batterham, AM, and Hanin, J. Progressive statistics for studies in sports medicine and exercise science. *Med Sci Sports Exerc* 41: 3–13, 2009.
16. de Hoyo, M, de la Torre, A, Pradas, F, Sañudo, B, Carrasco, L, Mateo-Cortes, J, and et al. Effects of eccentric overload bout on change of direction and performance in soccer players. *Int J Sports Med* 36: 308–314, 2014.
17. Impellizzeri, FM, Bizzini, M, Dvorak, J, Pellegrini, B, Schena, F, and Junge, A. Physiological and performance responses to the FIFA 11+ (part 2): A randomised controlled trial on the training effects. *J Sports Sci* 31: 1491–1502, 2013.
18. Linder, EE, Prins, JH, Murata, NM, Derenne, C, Morgan, CF, and Solomon, JR. Effects of preload 4 repetition maximum on 100-m sprint times in collegiate women. *J Strength Cond Res* 24: 1184–1190, 2010.
19. Low, D, Harsley, P, Shaw, M, and Peart, D. The effect of heavy resistance exercise on repeated sprint performance in youth athletes. *J Sports Sci* 33: 1028–1034, 2015.
20. Maroto-Izquierdo, S, García-López, D, Fernandez-Gonzalo, R, Moreira, OC, González-Gallego, J, and 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* 20: 943–951, 2017.
21. McBride, JM, Nimphius, S, and Erickson, TM. The acute effects of heavy-load squats and loaded countermovement jumps on sprint performance. *J Strength Cond Res* 19: 893–897, 2005.
22. Meylan, CMP, Nosaka, K, Green, J, and Cronin, JB. Temporal and kinetic analysis of unilateral jumping in the vertical, horizontal, and lateral directions. *J Sports Sci* 28: 545–554, 2010.
23. Moir, GL. Three different methods of calculating vertical jump height from force platform data in men and women. *Meas Phys Educ Exerc Sci* 12: 207–218, 2008.
24. Norrbrand, L, Pozzo, M, and Tesch, PA. Flywheel resistance training calls for greater eccentric muscle activation than weight training. *Eur J Appl Physiol* 110: 997–1005, 2010.
25. Okuno, NM, Tricoli, V, Silva, SBC, Bertuzzi, R, Moreira, A, and Kiss, MA. PDM. Postactivation potentiation on repeated-sprint ability in elite handball players. *J Strength Cond Res* 27: 662–668, 2013.
26. Rahnama, N, Reilly, T, Lees, A, and Graham-Smith, P. Muscle fatigue induced by exercise simulating the work rate of competitive soccer. *J Sports Sci* 21: 933–942, 2003.
27. Robbins, DW. Postactivation potentiation and its practical applicability: A brief review. *J Strength Cond Res* 19: 453–458, 2005.
28. Scott, SL and Docherty, D. Acute effects of heavy preloading on vertical and horizontal jump performance. *J Strength Cond Res* 18: 201–205, 2004.
29. Tous-Fajardo, J, Gonzalo-Skok, O, Arjol-Serrano, JL, and Tesch, P. Enhancing change-of-direction speed in soccer players by functional inertial eccentric overload and vibration training. *Int J Sports Physiol Perform* 11: 66–73, 2016.
30. Vicens-Bordas, J, Esteve, E, Fort-Vanmeerhaeghe, A, Bandholm, T, and 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* 21: 75–83, 2017.
31. Wagle, JP, Taber, CB, Cunanan, AJ, Bingham, GE, Carroll, KM, DeWeese, BH, et al. Accentuated eccentric loading for training and performance: A review. *Sports Med* 47: 2473–2495, 2017.
32. Wisløff, U, Castagna, C, Helgerud, J, Jones, R, and Hoff, J. Strong correlation of maximal squat strength with sprint performance and vertical jump height in elite soccer players. *Br J Sports Med* 38: 285–288, 2004.
33. Yoo, WG. Comparison of hamstring-to-quadriceps ratio between accelerating and decelerating sections during squat exercise. *J Phys Ther Sci* 28: 2468–2469, 2016.