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

MARCO BEATO,[1] ADAM STIFF,[1] AND GIUSEPPE CORATELLA[2]

*[1]School of Science, Technology and Engineering, University of Suffolk, Ipswich, United Kingdom; and [2]Department of Biomedical Sciences for Health, University of Milan, Italy*

## 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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Address correspondence to Marco Beato, M.Beato@uos.ac.uk.

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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

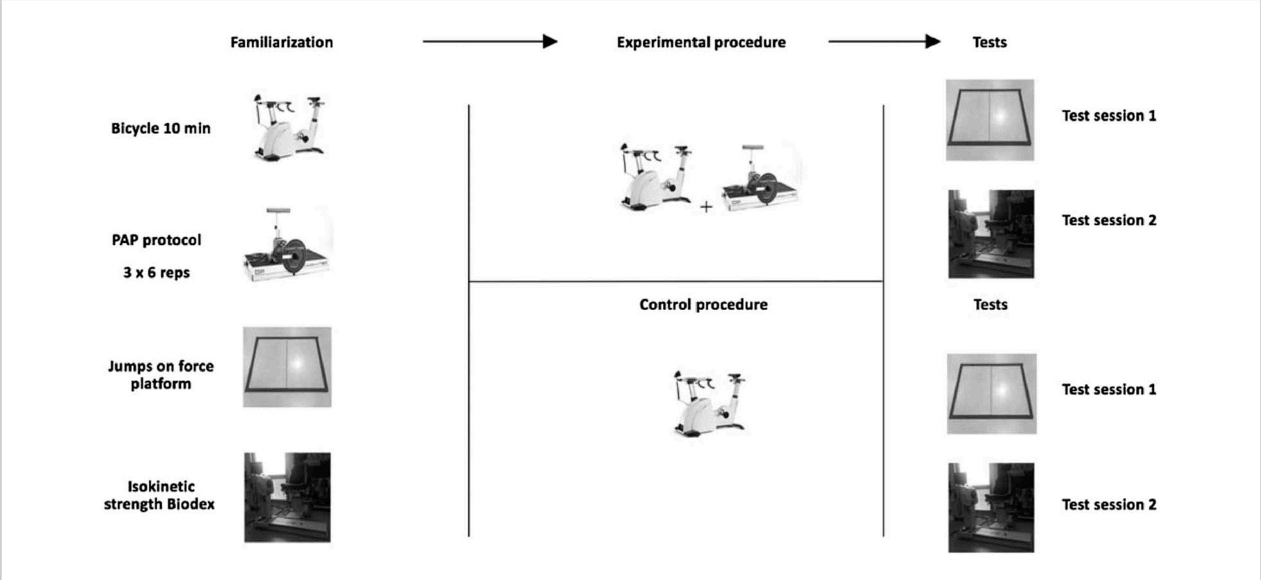

**Figure 1.** Experimental and control procedure.

**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 $\alpha$-error $\leq 0.05$, 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 ($60° \cdot s^{-1}$) | | | | | | |
| 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 ($60° \cdot s^{-1}$) | | | | | | |
| 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 ($60° \cdot s^{-1}$), and the hamstrings peak torque was measured in concentric ($60° \cdot s^{-1}$) and eccentric ($-60° \cdot s^{-1}$) 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.

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# Effects of in-season enhanced negative work-based vs traditional weight training on change of direction and hamstrings-to-quadriceps ratio in soccer players

**AUTHORS: Giuseppe Coratella[1], Marco Beato[2], Emiliano Cè[1,3], Raffaele Scurati[1], Chiara Milanese[4], Federico Schena[4], Fabio Esposito[1,3]**

[1] Department of Biomedical Sciences for Health, Università degli Studi di Milano, Italy
[2] Faculty of Health and Science, Department of Science and Technology, University of Suffolk, Ipswich, UK
[3] IRCSS Istituto Ortopedico Galeazzi, Milano, Italy
[4] Department of Neurological, Biomedical and Movement Sciences, Università degli Studi di Verona, Italy

Corresponding author:
**Giuseppe Coratella**
Department of Biomedical Sciences for Health, Università degli Studi di Milano, Italy
Mail address: via Giuseppe Colombo 71, 20133 Milano
Tel.: 0039-2-50314648
Fax: 0039-2-50315163
Email: giuseppe.coratella@unimi.it

**ABSTRACT:** The present study investigated the effects of in-season enhanced negative work-based training (ENT) vs weight training in the change of direction (COD), sprinting and jumping ability, muscle mass and strength in semi-professional soccer players. Forty male soccer players participated in the eight-week, 1 d/w intervention consisting of 48 squat repetitions for ENT using a flywheel device (inertia=0.11 kg·m$^{-2}$) or weight training (80%1 RM) as a control group (CON). Agility T-test, 20+20 m shuttle, 10 m and 30 m sprint, squat jump (SJ) and countermovement jump (CMJ), lean mass, quadriceps and hamstrings strength and the hamstrings-to-quadriceps ratio were measured. Time on agility T-test and 20+20 m shuttle decreased in ENT (effect-size =-1.44, 95% CI -2.24/-0.68 and -0.75, -1.09/-0.42 respectively) but not in CON (-0.33, -0.87/0.19 and -0.13, -0.58/0.32). SJ and CMJ height increased in both ENT (0.71, 0.45/0.97 and 0.65, 0.38/0.93) and CON (0.41, 0.23/0.60 and 0.36, 0.12/0.70). Overall, quadriceps and hamstrings strength increased in both ENT and CON (0.38/0.79), but the hamstrings-to-quadriceps ratio increased in ENT (0.31, 0.22/0.40) but not in CON (0.03, -0.18/0.24). Lean mass increased in both ENT (0.41, 0.26/0.57) and CON (0.29, 0.14/0.44). The repeated negative actions performed in ENT may have led to improvements in braking ability, a key point in COD performance. Semi-professional soccer players may benefit from in-season ENT to enhance COD and the negative-specific adaptations in muscle strength and hamstrings-to-quadriceps ratio.

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## INTRODUCTION

A flywheel device allows the negative [1] phase accumulated by the inertia during the positive phase to be emphasized [2]. The possibility to enhance the strength exerted during the negative phase has led several authors to investigate its acute or long-term adaptations [3–9]. Additionally, it was recently concluded that training that used a flywheel device compared with traditional weight training may lead to equal [10] or superior [11] muscle strength and mass gains. This is based on the significant contribution of the negative phase in gaining muscle strength [12], irrespective of the exercise modality performed [13].

Enhanced negative work-based training (ENT) demands the athletes to repeatedly brake the body-mass inertia and subsequently accelerate it; thus it has been recently argued that ENT might mimic the change of direction (COD) demands [14], given the repeated brakes and accelerations occurring during CODs [15]. It was hypothesized that emphasizing the negative phase might result in favourable adaptations in COD ability [14]. However, few recent studies have confirmed this link [16–18], while no adaptation in COD was also reported [5]. Therefore, the authors of the aforementioned review [14] encouraged further studies on the possible ENT-induced adaptations in COD ability. In team sports and particularly in soccer, CODs affect the physiological demands, since a COD-based fatiguing test resulted in minor increases in heart rate, blood lactate concentration and perceived fatigue in COD-accustomed soccer players vs non-COD-accustomed fitness-matched athletes [19]. Additionally, the intermittent and unpredictable nature of soccer requires the players to perform explosive high-intensity activities, such as changing direction, sprinting and jumping [15]. Lower-limb muscle strength training has been included in the traditional weekly soccer routine to improve COD, sprinting and jumping ability [20–23]. However, less is known about the effectiveness of including ENT within the in-season weekly routine, given the lower players' sensitivity to the training-induced adaptations reported in season [21] than pre-season [24].

Squatting involves mostly lower-limb muscles, with a special emphasis on quadriceps and hamstrings. Interestingly, greater hamstrings vs quadriceps activation was observed during the negative vs positive squatting phase [25]. Consequently, the different negative-to-positive activation ratio in ENT vs traditional weight training could lead to specific adaptations in hamstrings and quadriceps strength, affecting the hamstrings-to-quadriceps ratio, used to monitor the hamstrings injury risk [26]. Therefore, the aims of the present study were to compare the in-season effects of ENT vs traditional weight training on: i) COD, sprinting and jumping ability; ii) quadriceps and hamstrings strength, hamstrings-to-quadriceps ratio and lower-limb muscle mass.

## MATERIALS AND METHODS

### *Participants*

Forty male soccer players (age: 23±4 years, body mass: 77±5 kg; height: 1.80±0.11 m) volunteered to participate. The participants joined two Italian fourth-division (Serie-D) soccer clubs, which competed in the Italian soccer championship. Within the season, their typical training volume consisted of four training sessions (about 2 hours per session) plus one match per week on Sunday, from September to May. The participants had soccer experience of at least five consecutive years in youth or semi-professional soccer teams. Lower-limb muscular or joint injuries in the previous 12 months, cardio-pulmonary diseases, smoking or the use of drugs were listed as exclusion criteria. The present investigation was approved by the local Ethical Committee and was in line with the Declaration of Helsinki (1975) concerning the ethical standards in studies involving human subjects. Finally, the participants were carefully informed about any possible risks due to the investigation's procedures and they signed a written informed consent form. They were also informed that they were free to withdraw from the study at any time.

### *Procedures*

The present investigation was designed as a pre-post, parallel two-group randomized trial. The participants of the two soccer teams were randomly assigned to an ENT or traditional weight-training routine, used as a conventional training group (CON), i.e. the two teams had the same number of participants included in ENT or CON. The randomization followed two steps: 1) the players were randomized to two groups (1 and 2); 2) groups 1 and 2 were randomized as ENT or CON. Such a design was chosen to have an overall similar training routine in the two groups. No control group was used (i.e. players who did not perform any training), since it would have resulted in an unethical and impracticable approach [21], not suitable for the present in-season design. Thus, the players performed their weekly routine, including the dedicated strength session performed with either ENT or CON. To have a more ecological approach, the strength training session was placed in the middle of the week, according to the habitual coaches' scheduled routines. The weekly programme was planned with the clubs' staffs and is reported in Table 1.

**TABLE 1.** The in-season weekly programme for the semi-professional soccer players involved in the present study.

| Day | Training Programme |
|---|---|
| Monday | Free |
| Tuesday | **Starters:** Warm-up, 15 min;<br>Technical/tactical, 15 min;<br>Low-/moderate-intensity aerobic training, 15 min;<br>Strength training and injury prevention, 15 min.<br>**Non-Starters:** Warm-up, 15 min;<br>Technical/tactical, 15 min;<br>Play, 30 min;<br>High-intensity aerobic training, 20 min. |
| Wednesday | Strength training (ENT or CON) 20 min;<br>Warm-up, 10 min;<br>CODS and/or SSGs, 20 min;<br>Technical/tactical, 25min;<br>Play, 25 min. |
| Thursday | Warm-up, 15 min;<br>Technical/tactical, 30 min;<br>Play, 45 min. |
| Friday | Warm-up, 15 min;<br>Speed training (long and short), 15 min<br>Technical/tactical, 25 min;<br>Play, 15 min. |
| Saturday | Free |
| Sunday | Match |

ENT: enhanced-negative work-based training; CON: traditional weight training
CODs = Change of directions; SSGS = Small-sided games

The procedures lasted 10 weeks and were performed in season, from mid January to the end of March. The participants were instructed to avoid any further form of resistance workout for the entire duration of the investigation. In the first week, they were involved in three testing sessions. In the first session, they were familiarized with the squatting technique, isokinetic strength testing procedures, COD, sprinting and jumping ability testing procedures. During the second session, muscle architecture, lean mass (LM) and squat 1-RM were measured, and the participants were familiarized with the training protocols. During the third session, hamstrings and quadriceps isokinetic peak torque, COD, sprinting and jumping ability were measured. The intervention lasted eight weeks. Finally, the post-training testing measurements were conducted over two sessions. In the first one, LM, squat 1-RM and hamstrings and quadriceps isokinetic peak torque were measured. In the second session, COD, sprinting and jumping abilities were measured. Each assessment was performed by the same experienced operators, unaware of the participants' allocation, and interspersed by 30 min of passive recovery. COD, sprints and jumps were measured indoor, on a concrete surface.

### *Squat 1-RM*

The 1-RM is a valid lower-limb strength measurement [27]. Back-squat 1-RM was measured using an Olympic bar (20 kg), following previous procedures [24]. After a standardized warm-up, consisting of 30 weight-free squats, the 1-RM attempts started from 80% of the body mass, given the non-specific strength-training experience of the participants. Thereafter, an additional 5% of the load was added until failure. Each set was separated by 3 min of passive recovery. The time under tension (2 s for the positive and negative phase, 1 s for the isometric phase) was standardized. The trial was valid once the participant lowered the thighs parallel to the ground. Strong standardized encouragements were provided to maximally perform each trial. Squat 1-RM / body mass was calculated and inserted into the data analysis.

### *Isokinetic measurements*

An isokinetic dynamometer (Cybex Norm, Lumex, Ronkonkoma, USA) was used to measure quadriceps and hamstrings strength. The procedures followed previous protocols [28]. Briefly, the device was calibrated according to the manufacturer's procedures, and the centre of rotation was aligned with the tested knee [13]. The participants were seated on the dynamometer chair, with their trunk slightly reclined backwards and a hip angle of 85°. Two seatbelts secured the trunk and one strap secured the tested limb, while an additional lever secured the untested limb [29]. A standardized warm-up, consisting of three sets x 10 repetitions of weight-free squats, preceded the measures [24]. Quadriceps peak torque was measured in positive (60 $\text{deg}\cdot\text{s}^{-1}$) and negative (-60 $\text{deg}\cdot\text{s}^{-1}$) modality and hamstrings peak torque was measured in negative (-60 $\text{deg}\cdot\text{s}^{-1}$) modality, as previously assessed [24]. Each testing modality consisted of three maximal trials and was separated by 2 min of passive recovery. Strong standardized encouragements were provided to maximally perform each trial. The peak torque was then calculated and inserted into the data analysis. Finally, the negative-hamstrings to positive-quadriceps peak torque ratio ($H_{ecc}$:$Q_{conc}$) [26] was calculated. The dominant limb, defined as the preferred limb used to kick the ball, was tested [30]. *Excellent* test-retest reliability was found for all the isokinetic measurements ($\alpha$ = 0.900 - 0.944).

### *Lower-limb lean mass*

Total body and regional composition were evaluated using DXA, a total-body scanner (QDR Explorer_W, Hologic, MA, USA; fan-bean technology, software for Windows XP version 12.6.1), according to the manufacturer's procedures. The DXA body composition approach assumes that the body consists of three components that are distinguishable by their X-ray attenuation properties: fat mass, LM and bone mineral [31]. The scanner was calibrated daily against the standard supplied by the manufacturer to avoid possible baseline drift. Data were analysed using standard body-region markers and the whole lower-limb LM amount was reported in the data analysis [24].

### *Squat jump and countermovement jump*

The squat jump (SJ) and countermovement jump (CMJ) peak height was investigated using an infrared device (OptoJump, Microgate, Italy). In SJ, the participants were instructed to stand, flex the knees to approximately 90° and jump and to avoid any countermovement. In CMJ, they had to stand, reach a self-selected knee flexion and immediately jump. No knee flexion before the landing was allowed in both the SJ and CMJ, with arms on the hips. Three attempts were performed for each jump, and the peak height was inserted into the data analysis. Two minutes of passive rest separated each jump. *Excellent* reliability was found for the SJ ($\alpha$ = 0.938) and CMJ ($\alpha$ = 0.903).

### *Sprint and COD*

The time trials of the agility T-test, 20+20 m shuttle and 10 m and 30 m sprint [15] were separately investigated using an infrared device (Polifemo, Microgate, Italy). The participants were placed 30 cm behind the starting line, with their preferred foot in a forward position and autonomously started each trial. *Excellent* reliability was found for the 10 m and 30 m sprint ($\alpha$ = 0.920 and $\alpha$ = 0.902, respectively).

The agility T-test was performed turning right or left first, and the sum of the two trials was inserted in the data analysis [24, 28]. A detailed description of the protocol was reported previously [24, 28]. The trials were not considered if participants failed to touch a designated cone or failed to face forward at all times. Only one timing gate placed on the start-finish line was used for timing the T-test. Each test was repeated three times, and the best performance was calculated and inserted into the data analysis. Two minutes of passive rest separated each trial. The agility T-test showed *good* reliability ($\alpha$ = 0.884).

The 20+20 m shuttle test was performed using two timing gates 20 m apart and a cone was placed 1 m beyond the second gate. The participants stood behind the first gate and had to sprint towards the second gate, touch the cone and sprint back to the first gate. The trial was not valid if participants failed to touch the cone. *Good* reliability ($\alpha$ = 0.867) was observed.

### *Intervention*

The intervention was performed 1 d/w (Table 1). The ENT squat was performed using a flywheel ergometer (D11 full, Desmotec, Biella, Italy), while the CON squat was performed using an Olympic bar (Technogym, Cesena, Italy). Both ENT and CON sessions started with 20 weight-free squats. Then, ENT performed 10 submaximal flywheel squats and CON performed 10 squats with 50% 1-RM. The intervention consisted of four sets in the first week, five sets in the second week and six sets in the remaining weeks of eight repetitions for both ENT (inertia: 0.11 kg·m$^{-2}$) and CON (80% 1-RM), interspersed by 3 min of passive recovery. The latter followed the specific seasonal strength protocol scheduled during the intervention period. The ENT inertial load was selected to have a similar muscle activity to result in a similar number of repetitions compared to CON [32]. ENT performed the positive phase as fast as possible and control the braking phase until the thighs were parallel to the ground. CON performed both the positive and the negative phase in approximately 2 s each, with a 1 s isometric stop when the thighs were parallel to the ground. A mirror was placed opposite to the participants to let them visually check their technique [7]. The participants received strong standardized encouragements to maximally perform each repetition.

### *Statistical analysis*

Statistical analysis was performed using statistical software (SPSS 22, IBM, USA). The normality of the distribution was checked using the Shapiro–Wilk test. The test–retest reliability was measured using an intraclass correlation coefficient (ICC, 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* [33]. The variations in the dependent parameters were analysed by separate mixed-factors ANOVA (time × group) for repeated measurements. Post-hoc analysis using Bonferroni's correction was then performed to calculate the main effect for group (two levels: ENT and CON) and time (two levels: pre- and post-training). To detect the between-group differences in the training-induced percentage changes, the data were first log-transformed, and then an analysis of covariance (ANCOVA) was performed, assuming baseline values as covariates. Significance was set at $\alpha<0.05$. Descriptive statistics are reported as mean with standard deviation (SD). Changes are reported as %change with 95% confidence intervals (CI95%) and effect size (ES) with CI95%. ES was interpreted as follows [34]: 0.00–0.19: *trivial*; 0.20–0.59: *small*; 0.60–1.19: *moderate*; 1.20–1.99: *large*; ≥2.00: *very large*.

## RESULTS

Time x group interactions were found for 20+20 m shuttle (F=5.568, p=0.028) and agility T-test (F=8.342, p=0.013), with *moderate* and *large* time decreases observed in ENT and non-significant *trivial* and *small* changes observed in CON, respectively (Table 2). No interaction was found for 10 m (F=3.122, p=0.168) or 30 m sprint

**TABLE 2.** Mean values (SD) of performances in COD, sprinting and jumping pre- and post-training are shown. Changes (%) and effect size are reported with confidence interval (CI95%).

| | Pre: Mean (SD) | Post: Mean (SD) | Change (%) (CI95%) | Effect size (CI95%) |
|---|---|---|---|---|
| **Shuttle 20+20 m (s)** | | | | |
| ENT | 7.88(0.41) | 7.52(0.32) | -4 (-6 to -2)*# | -0.75 (-1.09 to -0.42) |
| CON | 7.91(0.45) | 7.85(0.47) | -1 (-6 to 4) | -0.13 (-0.58 to 0.32) |
| **Agility T-test (s)** | | | | |
| ENT | 15.9(0.7) | 14.8(0.8) | -7 (-12 to -2)*# | -1.44 (-2.24 to -0.68) |
| CON | 15.8(0.8) | 15.5(0.9) | -2 (-9 to 5) | -0.33 (-0.87 to 0.19) |
| **10 m sprint (s)** | | | | |
| ENT | 1.93(0.13) | 1.90(0.08) | -2 (-5 to 2) | -0.23(-0.65 to 0.18) |
| CON | 1.91(0.12) | 1.89(0.12) | -1 (-4 to 3) | -0.12(-0.34 to 0.10) |
| **30 m sprint (s)** | | | | |
| ENT | 4.54(0.23) | 4.47(0.20) | -2 (-3 to -0) | -0.32 (-0.60 to 0.04) |
| CON | 4.58(0.25) | 4.59(0.22) | -0 (-6 to 6) | -0.01 (-0.33 to 0.35) |
| **SJ (cm)** | | | | |
| ENT | 37.6(5.8) | 41.8(5.9) | 11 (6 to 16)* | 0.71 (0.45 to 0.97) |
| CON | 38.2(6.3) | 40.8(6.7) | 7 (4 to 10)* | 0.41 (0.23 to 0.60) |
| **CMJ (cm)** | | | | |
| ENT | 39.5(7.1) | 43.5(6.9) | 10 (7 to 14)* | 0.65 (0.38 to 0.93) |
| CON | 39.9(7.4) | 42.6(7.7) | 7 (3 to 11)* | 0.36 (0.12 to 0.70) |

ENT: enhanced-negative work-based training; CON: traditional weight training.
SJ: Squat jump; CMJ: counter-movement jump.
* = $p < 0.05$ compared to pre; # = $p < 0.05$ compared to CON.

(F=2.941, p=0.201) and neither ENT nor CON experienced decreases in 10 m or 30 m time. (Table 2). Lastly, no time x group interaction was found for SJ (F=2.392, p=0.303) or CMJ (F=2.583, p=0.281). ENT and CON experienced *moderate* and *small* increases respectively in both SJ and CMJ peak height, with a between-group difference observed (Table 2).

Time x group interactions were found for quadriceps positive (F=5.021, p=0.042) and negative peak torque (F=5.439, p=0.031) and for $H_{ecc}$:$Q_{conc}$ ratio (F=9.847, p=0.010). CON showed a *moderate* increase in quadriceps positive peak torque, greater than the *small* increase observed in ENT (+6%, CI95% 2/10) (Table 3). The *moderate* increase in quadriceps negative peak torque observed in ENT was greater than the *small* increase observed in CON (+7%, CI95% 3/11). ENT showed a *small* increase in $H_{ecc}$:$Q_{conc}$ ratio. No group x time interaction occurred for squat 1-RM (F=3.233, p=0.218) or hamstrings negative peak torque (F=1.744, p=0.716). *Small* and *moderate* increases in squat 1-RM were found in ENT and CON respectively, while both ENT and CON had *small* increases in negative peak torque (Table 3). No time x group interaction was found for lower-limb LM (F=1.956, p=0.651). *Small* increases in lower-limb LM occurred in both ENT and CON (Table 3).

## DISCUSSION

The current investigation highlighted that an in-season ENT vs CON intervention induced different adaptations in semi-professional soccer players. *Moderate*-to-*large* improvements in COD ability were observed only in ENT, with non-significant *trivial*-to-*small* changes in CON. No effect on sprinting ability was observed in ENT or CON. *Moderate* and *small* increases in SJ and CMJ peak height were observed in ENT and CON, with no between-group difference. Lastly, ENT showed *moderate* increases in quadriceps and hamstrings negative peak torque and a *small* rise in quadriceps positive peak torque and squat 1-RM. In contrast, CON showed *moderate* increases in squat 1-RM, quadriceps positive and hamstrings negative peak torque, accompanied by a *small* increase in quadriceps negative peak torque. This led to a *small* increase in $H_{ecc}$:$Q_{conc}$ ratio observed only in ENT. Concurrently, *small* significant increases in lower-limb LM occurred in both ENT and CON.

When changing direction, strongly decelerating and accelerating immediately after is required. In line with the current outcomes, ENT improved COD in elite U18 soccer players [16]. This may depend on the decreased time spent to brake and increased braking impulse observed after ENT [18]. Consequently, the repetitive braking actions

**TABLE 3.** Mean values (SD) of quadriceps and hamstrings strength pre- and post-training are shown. Changes (%) and effect size are reported with confidence interval (CI95%).

| | Pre: Mean (SD) | Post: Mean (SD) | Change (%) (CI95%) | Effect size (CI95%) |
|---|---|---|---|---|
| **Squat 1-RM ($Kg \cdot BM^{-1}$)** | | | | |
| ENT | 1.21(0.20) | 1.30(0.22) | 7 (2 to 12)* | 0.40 (0.15 to 0.75) |
| CON | 1.18(0.14) | 1.33(0.21) | 13 (6 to 20)* | 0.73 (0.34 to 1.07) |
| **Quadriceps PPT (N·m)** | | | | |
| ENT | 226(39) | 241(40) | 7 (2 to 11)*# | 0.39 (0.13 to 0.65) |
| CON | 231(40) | 264(41) | 13 (5 to 21)* | 0.80 (0.32 to 1.28) |
| **Quadriceps NPT (N·m)** | | | | |
| ENT | 281(62) | 330(63) | 17 (10 to 24)*# | 0.79 (0.49 to 1.09) |
| CON | 276(63) | 301(64) | 9 (2 to 16)* | 0.39 (0.08 to 0.70) |
| **Hamstrings NPT (N·m)** | | | | |
| ENT | 195(46) | 218(53) | 12 (5 to 18)* | 0.50 (0.27 to 0.73) |
| CON | 191(46) | 214(49) | 12 (3 to 21)* | 0.48 (0.14 to 0.82) |
| **$H_{ecc}$:$Q_{conc}$ (A.U.)** | | | | |
| ENT | 0.88(0.22) | 0.94(0.18) | 7 (4 to 10)*# | 0.31 (0.22 to 0.40) |
| CON | 0.82(0.31) | 0.81(0.29) | 1 (-6 to 8) | 0.03 (-0.18 to 0.24) |
| **Lean mass (Kg)** | | | | |
| ENT | 21.3(2.6) | 22.4(2.8) | 5 (3 to 7)* | 0.41 (0.26 to 0.57) |
| CON | 21.5(2.7) | 22.3(2.7) | 4 (2 to 6)* | 0.29 (0.14 to 0.44) |

ENT: enhanced-eccentric work-based training; CON: traditional weight training.
BM: body mass; PPT: positive peak-torque; EPT: negative peak-torque.
* = $p < 0.05$ compared to pre; # = $p < 0.05$ compared to CON

performed in the agility T-test vs the single turning action performed in the 20+20 m shuttle may have increased the extent of ENT-induced adaptations (*large vs moderate*, respectively) in ENT. Instead, the absence of enhanced negative actions in CON led to *trivial* changes in 20+20 m shuttle and non-significant *small* changes in agility T-test. No improvement in agility after strength training was also reported in elite soccer players [35]. In contrast, COD ability improved after long-term strength training added to the traditional weekly routine [36] or after an eight-week programme in junior soccer players [37]. However, the former involved the participants in a two-season training programme [36], while the latter involved young players who were likely unaccustomed and consequently more sensitive to strength training [37]. Thus, it seems that a traditional short-term strength-training programme does not appropriately stimulate the COD ability in accustomed soccer players. However, enhancing the negative phase may elicit the braking ability and transfer this to COD.

Non-significant *small* and *trivial* decreases in 10 m and 30 m sprint occurred in ENT and CON respectively. Traditional low-velocity resistance training was not effective in improving sprinting ability in physically active men [38]. In contrast, decreases in linear sprint time were reported in elite soccer players [20]. However, it should be acknowledged that the present procedures involved the participants in one single strength training session, in contrast with the two or more sessions in the previous study [20]. Additionally, this latter study used moderate intensity (40–60% 1-RM) that allowed very fast positive actions. Indeed, explosive training led to decreases in 10 m and 30 m sprint time [24, 38]. However, despite the explosive nature of the positive phase in ENT, the changes were not significant. Partially in line with the present outcomes, no change in 20 m sprint time occurred after specific resisted horizontal inertial flywheel training [5]. In contrast, two-to-three ENT sessions per week were reported to favourably affect the sprinting ability in handball players [11]. Therefore, it might be argued that one session per week might not be a sufficient stimulus to improve the linear sprinting ability when performed in season.

*Moderate* and *small* increases in SJ and CMJ peak height occurred in ENT and CON, respectively. Lower-limb muscle strength was reported to be correlated with jumping ability [39]. However, traditional weight training had a poor transfer to jumping ability, in favour of more explosive actions [23]. Indeed, training using loads that elicit maximum power was effective in increasing vertical jump height [24, 38] and the explosive nature of the positive phase in ENT was shown to increase muscle power [40], which turned into increases in SJ and CMJ height [6]. Notwithstanding, given the extent of the changes in sprinting and jumping ability in both groups, it should be remarked that the present investigation was conducted in season, i.e. a period in which the players are less sensitive to the training-induced improvements [21, 22].

Both ENT and CON increased hamstrings and quadriceps strength. However, this seemed to have followed specific training-testing adaptations; i.e. greater improvements occurred in the test that was similar to the training. Indeed, ENT quadriceps negative peak torque increased *moderately* compared to the *small* increases in quadriceps positive peak torque and squat 1-RM. Similarly, CON *moderately* increased quadriceps positive peak torque and squat 1-RM, while quadriceps negative peak torque increased by a *small* extent. The greater increases in quadriceps negative vs positive strength after negative-based training have already been reported [13, 41], as well as the greater increases in positive strength after positive-based training [42]. Interestingly, two different meta-analyses reported no difference [10] or greater strength increases [11] after ENT vs traditional weight training. Such discordance can be due to the studies' inclusion/exclusion criteria, as well as the several modalities used to assess muscle strength. Importantly, the strength training-testing specificity should be considered when measuring resistance training-induced adaptations [12]. The greater increases in quadriceps positive peak torque in ENT than CON might be related to the improvements in COD ability in ENT. Intriguingly, only ENT induced an increase in the $H_{ecc}$:$Q_{conc}$ ratio, mainly due to the greater increases in quadriceps positive vs hamstrings negative peak torque in CON. This is associated with the greater hamstrings vs quadriceps activation recorded during the negative squat phase [25]. Although no previous study has directly investigated this, the current outcomes agree with the greater $H_{ecc}$:$Q_{conc}$ ratio induced by greater negative inertia [24]. Hamstrings negative strength could help to monitor the strain injury risk, although this is a multifactorial phenomenon [43].

*Small* increases in lower-limb LM occurred in both ENT and CON. A minimum of 4-week strength training duration is needed to observe a hypertrophic response [44]. However, in an unaccustomed population, ENT caused an hypertrophic response in three weeks, even though the total number of sessions was similar to the present study [4]. Negative training is a powerful stimulus for increasing muscle size [12], even in trained populations [45]. Notwithstanding, ENT was not shown to be superior to traditional weight training [10]. Interestingly, one session/week effectively promotes muscle hypertrophy [44]. Particularly, the authors pointed out that higher frequency did not result in a greater muscle size increase when volume-equated. However, two further considerations need to be made. Firstly, the participants were involved in an in-season intervention, so less sensitive to the training-induced adaptations. Secondly, it cannot be excluded that a second session (thus increasing the volume) could have resulted in greater increases in LM. However, given the ecological procedures, this was not possible.

The present investigation has some limitations. Firstly, a methodological consideration needs to be acknowledged. Although the procedures were conducted to have similar between-group training volume, this might not have resulted in a perfectly equated amount of work. This occurs because, while traditional weight training volume could be calculated *a priori*, this is not possible using a flywheel device. However, the two loads used have a similar relative intensity [32]. Additionally, the whole weekly load could have been somewhat different between the two teams, although the authors together with the teams' staff carefully checked this. However, we are confident that the similar teams' level and in-season period might have resulted in a similar weekly load. Secondly, no control group was included. Although it could have reinforced the study design, it was not ethically acceptable to interrupt the in-season routine, and the clubs and the coaches would have refused their consent. Thirdly, power data were not collected. Although this could have reinforced the methodological procedures, such a technology is not often available among semi-professional teams. Lastly, given the specific routine used here, these data may only refer to semi-professional players. Further studies are needed to investigate the effects of ENT vs CON in different soccer populations.

## CONCLUSIONS

The present outcomes suggest that a single weekly ENT session improved COD. In contrast, higher-frequency resistance training is needed to improve the sprinting ability in season [20]. In addition, the specific ENT-induced increases in $H_{ecc}$:$Q_{conc}$ ratio leads to interesting injury prevention perspectives. Although specific exercises have been proposed to increase hamstrings strength (e.g. Nordic hamstrings), a non-specific ENT squat may be proposed for this aim. However, when a flywheel device is not available, a traditional squat should be coupled with hamstrings reinforcement.

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### Conflict of interests

The authors declare no conflict of interests.

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RESEARCH ARTICLE

# Post-activation potentiation effect of eccentric overload and traditional weightlifting exercise on jumping and sprinting performance in male athletes

**Marco Beato**[1]*, **Alexander E. J. Bigby**[1], **Kevin L. De Keijzer**[1], **Fabio Y. Nakamura**[2,3], **Giuseppe Coratella**[4], **Stuart A. McErlain-Naylor**[1]

**1** School of Health and Sports Sciences, University of Suffolk, Ipswich, United Kingdom, **2** Associate Graduate Program in Physical Education UPE/UFPB, João Pessoa, PB, Brazil, **3** The College of Healthcare Sciences, James Cook University, Townsville, Australia, **4** Department of Biomedical Sciences for Health, University of Milan, Milan, Italy

* M.Beato@uos.ac.uk

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## Abstract

The aim of this study was to evaluate the post-activation potentiation (PAP) effects following eccentric overload (EOL) and traditional weightlifting (TW) exercise on standing long jump (SLJ), countermovement jump (CMJ), and 5 m sprint acceleration performance. Ten male athletes were involved in a randomized, crossover study. The subjects performed 3 sets of 6 repetitions of EOL or TW half squat exercise followed by SLJ, CMJ, and 5 m sprint tests at 1 min, 3 min and 7 min, in separate sessions using a randomized order. Bayes factor ($BF_{10}$) was reported to show the strength of the evidence. Differences were found using EOL for SLJ distance at 3 min ($BF_{10} = 7.24$, +8%), and 7 min ($BF_{10} = 19.5$, +7%), for CMJ at 3 min ($BF_{10} = 3.25$, +9%), and 7 min ($BF_{10} = 4.12$, +10.5%). Differences were found using TW exercise for SLJ at 3 min ($BF_{10} = 3.88$, +9%), and 7 min ($BF_{10} = 12.4$, +9%), CMJ at 3 min ($BF_{10} = 7.42$, +9.5%), and 7 min ($BF_{10} = 12.4$, +12%). No meaningful differences were found between EOL and TW exercises for SLJ ($BF_{10} = 0.33$), CMJ ($BF_{10} = 0.27$), and 5 m sprint ($BF_{10} = 0.22$). In conclusion, EOL and TW exercises acutely increase SLJ and CMJ, but not 5 m sprint performance. The PAP time window was found between 3 min and 7 min using both protocols. This study did not find differences between EOL and TW exercises, and so both methodologies can be used to stimulate a PAP response.

## Introduction

Post-activation potentiation (PAP) is a physiological phenomenon associated with an acute improvement in muscular performance after a resistance training protocol [1,2]. Neuromuscular, mechanical and biochemical changes may induce these temporary improvements in performance but the exact underlying mechanisms are still not fully understood [1,3]. The most strongly supported explanation for the effects of PAP relates to a greater rate of cross-bridge

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attachment as a result of phosphorylation of myosin regulatory light chains during muscle contraction [4]. Furthermore, PAP is proposed to result from increased sensitivity of contractile proteins to calcium ($Ca^{2+}$) released from the sarcoplasmic reticulum, resulting in a cascade of events leading to an enhanced muscular response [3–5].

PAP may be induced through the use of resistance training exercises prior to the main sport-specific activity, leading to an increase in performance [6]. Generally, following a preload exercise, a temporary fatigue-induced decrement in performance is observed, which is subsequently replaced by a PAP response [3,7]. Traditional weightlifting (TW) is one of the modalities used by coaches to elicit a PAP response for subsequent competitive activities [3]. The majority of research investigating TW and its PAP response has reported a positive effect on reducing short distance sprint time and improving countermovement jump (CMJ) performance [3,8]. Both heavy and moderate load back squat (90% and 60% 1RM, respectively) have been shown to potentiate the sprinting and jumping performance of male professional rugby players [9]. Some previous studies on acute lower limb performance have found positive improvements after traditional pre-load strategies, while others have failed to confirm such results [3]. Such discrepancies may be a result of differences in the interventions relating to protocol characteristics including exercise modality, volume, intensity, muscle action, and duration of rest between the pre-load exercise and the subsequent sport-specific task, all of which have been identified as key variables determining the magnitude of a PAP response [6,10].

Flywheel ergometers are commonly used in sports training to chronically improve elite soccer players' jump and sprint performances [1,11,12]. Such devices are capable of stimulating an eccentric overload (EOL), in which the generated eccentric muscular force exceeds the maximal concentric force [13,14]. The user rotationally accelerates the flywheel with maximal velocity during the concentric phase of the movement (*e.g.* extension phase of a squat), resulting in a flywheel inertial torque that imparts high linear resistance during the subsequent eccentric phase of the movement (*e.g.* flexion phase of a squat) [1,11,12]. The main advantage of this exercise methodology is related to the high mechanical overload of the eccentric phase, which may enable strength and conditioning practitioners to improve athletes' performances both chronically and acutely [7,12]. Indeed, the greater eccentric load may recruit higher order motor units or fast-twitch muscle fibers at a greater extent and therefore likely facilitate a greater PAP response in subsequent sport-specific performance [4]. Moreover, eccentric load generated by a flywheel device may contribute to acutely improving stretch-shortening cycle performance and transfer effects on the explosive athletic tasks such as vertical jumps, horizontal jumps and sprinting [7,14,15].

Very few studies have evaluated the acute PAP induced improvement in lower limb performance following flywheel exercise [16]. Recently, acute sprint (20 m) and CMJ performance improvements have been found after EOL exercise [1]. Similar EOL-induced PAP improvements were reported in quadriceps concentric peak torque, hamstring concentric and eccentric peak torque during an isokinetic test ($60^{\circ}\cdot s^{-1}$) [7]. Moreover, augmented CMJ height, impulse, peak power and peak force were observed following the same EOL exercise protocol [7]. This study reported that PAP improves lower limb performance after 3 minutes of recovery following a flywheel squat exercise, with optimal time windows from 3 to 9 min. Previous studies using TW exercises have revealed inconsistent findings since several confounding factors may affect PAP response [4]. Indeed, PAP response may be affected by subjects' resistance training experience and competitive level [3,8]. It is not currently well established whether EOL is a more beneficial methodology to increase PAP and consequent lower-limb performance than TW, or *vice versa*. Such a comparison may have several practical applications in strength and conditioning in sport as well as for warm-up strategies before some competitions.

EOL and TW may be valid strategies to elicit acute PAP mediated improvements in lower limb power and therefore may play a functional role in sports performance training. Standing long jump (SLJ), CMJ and sprinting are well established tests to assess the lower-limb capacities. The aims of this study were: firstly, to study the acute effect of EOL and TW exercise on such sport-specific tasks; and secondly, to compare the magnitude of such acute effects between EOL and TW exercises. Such knowledge may be relevant for practitioners in order to generate PAP strategies prior to competition and training. Considering the greater peak power generated during the eccentric phase of the squat exercise, it could be supposed that EOL exercise may produce a higher PAP response in the subsequent sport-specific tasks than TW. However, authors hypothesize that both protocols should stimulate a positive PAP response in jumping and sprinting performance.

## Materials and methods

### Subjects

Ten male amateur athletes were enrolled in this study (mean ± SD: age 22 ± 2 years; body mass 73.2 ± 8.0 kg; height 1.79 ± 0.05 m) with $\geq$ 4 years experience with heavyweight training at a regional level. Inclusive criteria for participation were the absence of any injury or illness and regular participation in training activities (a minimum of 3 training sessions per week) as used in previous research [7]. A Bayesian adaptive sample size approach was used in this study to estimate the number of subjects [17] based on previous research of the same group [14]. Subjects were familiar with TW and EOL exercises and test procedures. All subjects were informed about the potential risks and benefits of the current procedures and gave their written informed consent. 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.

### Experimental overview

The acute effects of EOL *vs* TW exercise on SLJ, CMJ, and 5 m sprint performance were investigated in the present randomized, cross-over study design. Each subject attended the laboratory on seven separate occasions. This was necessary to remove a possible transient fatigue effect. The sessions were separated by 48 h of recovery to allow an adequate recovery period. Researchers required subjects to maintain their normal nutritional intake during the experimental period. Alcohol and caffeine were not permitted prior to the experimental sessions but hydration was allowed during the sessions. In the first session subjects performed the baseline condition and familiarization to EOL and TW [14]. During the baseline conditions athletes performed the same warm-up protocol utilized during the experimental condition but without any pre-load exercise (neither EOL or TW). In each of the following sessions (sessions were performed in a randomized order using Randomization.com, in order to remove any possible learning effect), the subjects performed the warm-up procedure utilized during the baseline condition followed by one of the two exercise modalities (EOL and TW). At 1 min, 3 min and 7 min after completion of the final EOL or TW set, one of the three performance tests (SLJ, CMJ, or 5 m linear sprint acceleration) were performed to evaluate the PAP effect (procedure reported in Fig 1). The authors considered that use of this protocol limited the confounding effect of repeated jumps as previously reported [7,14]. These time windows were used to observe PAP optimization, as used with success in previous studies [3,7].

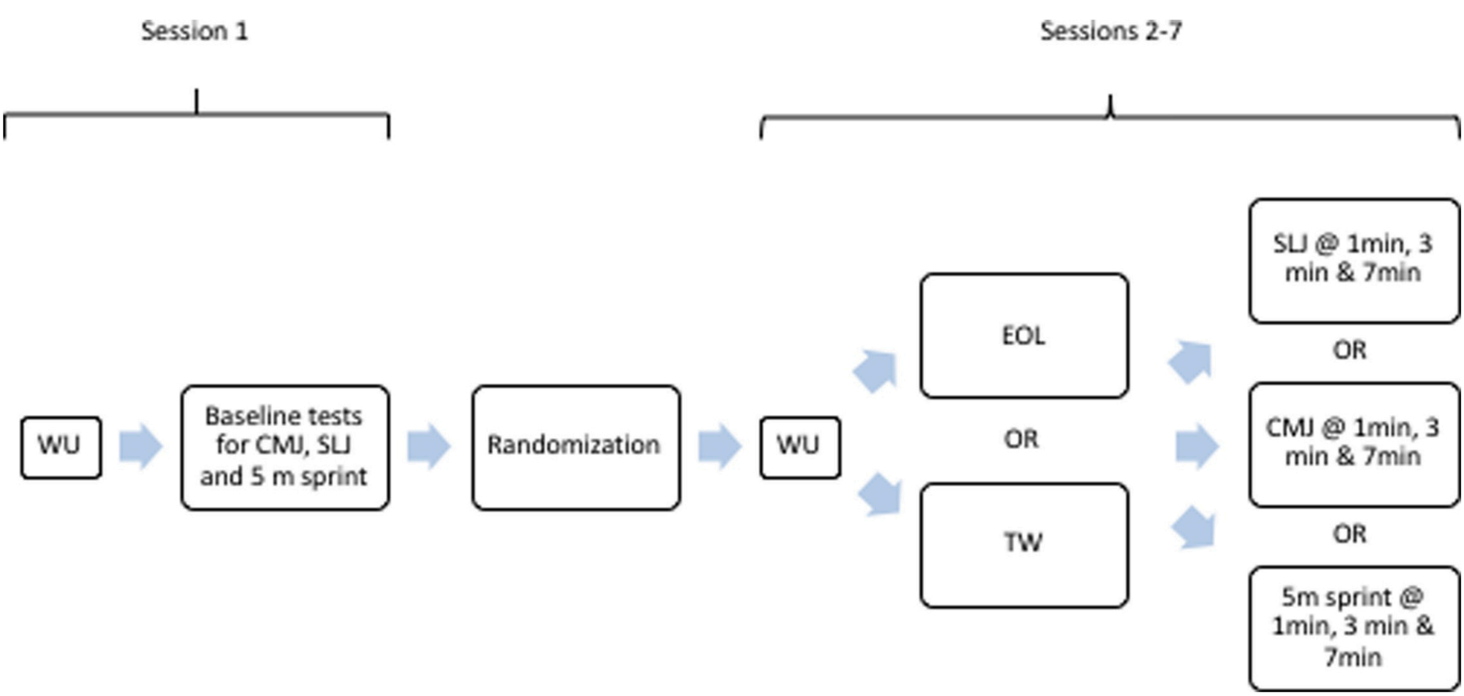

**Fig 1. Experimental procedure.** CMJ = Countermovement jump, SLJ = Standing Long jump, min = minutes, EOL = Eccentric overload, TW = Traditional weightlifting.

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## Procedures

Body mass and height were recorded by Stadiometer (Seca 286dp, Hamberg, Germany). A standardized warm-up was conducted each session, including 10 min of cycling at a constant power (1 W per kg of subject's body mass) on an ergometer (Sport Excalibur lode, Groningen, Netherland). Dynamic mobilization was performed in both the baseline and experimental conditions. Mobilization was performed immediately after the cycling warm-up for a duration of 3 minutes and consisted of dynamic movements mimicking the exercise (*e.g.* half squat) and dynamic hip, knee, and ankle movements. Such procedure was utilized prior to baseline tests as previously utilized by the same research group [14].

A SLJ was utilized to test the explosive horizontal power capabilities of the lower limb musculature, as previously reported [18]. Subjects performed one maximal bilateral anterior jump with arm swing. Jump distance was measured from the starting line to the point at which the heel contacted the ground on landing [19]. The validity of this test was previously reported in the literature involving a sample of physical education students [20]. An *excellent* (ICC = 0.90) baseline test-retest intrasession reliability was found in the current study. The smallest worthwhile change (SWC) was 5 cm for SLJ.

CMJ height was investigated using an infrared device (OptoJump, Microgate, Bolzano, Italy). The subjects were instructed to stand, lower themselves to a self-selected depth and immediately jump. Arms were placed on the hips to minimize the confounding effects of arm swing and the subjects were instructed to minimize knee flexion before landing. An *excellent* (ICC = 0.92) baseline test-retest intrasession reliability was found in the current study. The SWC was 1.2 cm for CMJ.

Five-meter sprints were performed to evaluate improvements in acceleration ability. Infrared timing gates (Microgate, Bolzano, Italy) were placed at the start and end of a measured 5 m distance. On the "Go" command, the subjects were instructed to sprint through the timing gates positioned as previously reported in literature [21]. No countermovement before the sprint was permitted. A *good* (ICC = 0.86) test-retest intrasession reliability was found in the current study. The SWC was 0.03 s for 5 m sprint performance.

## Intervention

EOL half squat exercise was performed using a flywheel ergometer (D11 Full, Desmotec, Biella, Italy). The protocol consisted of 3 sets x 6 repetitions of half squats, interspersed by 2 min of passive recovery [7]. The subjects were instructed to perform the concentric phase with maximal velocity and to control the eccentric phase until the knees where flexed to approximately 90° [14]. The following load was used for each subject: one Pro disc (diameter = 0.285 m; mass = 6.0 kg; moment of inertia = 0.06 $kg \cdot m^2$) based on previous published research [14]. The moment of inertia of the ergometer was estimated as 0.0011 $kg \cdot m^2$. Power was calculated for each repetition using an integrated rotary position transducer.

TW was performed as a half squat exercise using an Olympic bar. The PAP protocol consisted of 3 sets x 6 repetitions of half squats, interspersed by 2 min of passive recovery [3]. The subjects were instructed to perform the concentric phase with maximal velocity and to control the eccentric phase until the knees were flexed to approximately 90° [22]. During the familiarization session, the TW squat loads were adjusted in order to match the peak concentric power production between TW and EOL. This was achieved by increasing the barbell load by 5 kg until the concentric peak power was within 10% of that of the EOL. The mean load was 57.7 ± 10.1 kg. Lower limb power was assessed during TW exercise by a linear position transducer (Cronojump, Barcelona, Spain).

The EOL (1097 ± 341 W, 14.98W/Kg) and TW (1030 ± 298 W, 14.07 W/Kg) concentric peak power during load matching were not meaningfully different between the conditions: Bayes factor ($BF_{10}$) = 0.88 (*anecdotal*; effect size = 0.51; 95% credible interval [CI]: -0.20, 1.35). The EOL (1138 ± 263 W) and TW (798 ± 286 W) eccentric power were meaningfully different: $BF_{10}$ = 44.42 (*very strong*; effect size = 1.88; 95% CI: 0.61, 3.05).

## Statistical analysis

Data were presented as mean ± SD. The test–retest intrasession reliability (during baseline session) was assessed using an intraclass correlation coefficient (ICC) and interpreted as follows: $ICC \geq 0.9$ = *excellent*; $0.9 > ICC \geq 0.8$ = *good*; $0.8 > ICC \geq 0.7$ = *acceptable*; $0.7 > ICC \geq 0.6$ = *questionable*; $0.6 > ICC \geq 0.5$ = *poor*; $ICC < 0.5$ = *unacceptable* [23]. A fully Bayesian statistical approach to provide probabilistic statements was used in this study [24]. Each analysis was conducted with a "noninformative" prior (Cauchy, 0.707). Bayesian repeated measures ANOVA was used to evaluate the effects of time (within; baseline, 1 min, 3 min, 7 min) and exercise modality (between; EOL vs TW) on each of SLJ, CMJ, and 5 m sprint performance. If a meaningful $BF_{10}$ was found, a Bayesian post-hoc was performed [25]. Markov Chain Monte Carlo with Gibbs sampling was used to make inferences (10000 samples) [26]. Estimates of median standardized effect size and 95% credible interval were calculated. Evidence for the alternative hypothesis ($H_1$) was set as $BF_{10} > 3$ and evidence for null hypothesis was set as $BF_{10} < 1/3$ [27]. $BF_{10}$ was reported to indicate the strength of the evidence for each analysis (between and within). The $BF_{10}$ was interpreted using the following evidence categories: $1 < BF_{10} < 3$ = *anecdotal* evidence for $H_1$; $BF_{10} \geq 3$ = *moderate*; $BF_{10} \geq 10$ = *strong*; $BF_{10} \geq 30$ = *very strong*; $BF_{10} \geq 100$ = *extreme* [27]. SWC was calculated as 0.2 x SD for SLJ, CMJ and 5 m sprint performance. Statistical analyses were performed within JASP (Amsterdam, Netherland) software Version 0.9.1.

## Results

The repeated ANOVA reported differences within (time) using EOL exercise for SLJ ($BF_{10}$ = 354.2, *extreme*), CMJ height ($BF_{10}$ = 698.3, *extreme*), but not in 5 m sprint ($BF_{10}$ = 0.61, *anecdotal*). The repeated ANOVA reported differences within (time) using TW exercise for SLJ ($BF_{10}$ = 193.1, *extreme*), CMJ height ($BF_{10}$ = 6967.3, *extreme*), but not in 5 m sprint ($BF_{10}$ = 0.37, *anecdotal*). A graphical representation of time effect on SLJ, CMJ and 5 m sprint was reported in Figs 2–4. No meaningful time x condition interactions were reported for any parameter analyzed: SLJ ($BF_{10}$ = 0.182, *moderate* in favor of $H_0$); CMJ ($BF_{10}$ = 0.159, *moderate* in favor of $H_0$); 5 m sprint ($BF_{10}$ = 0.049, *moderate* in favor of $H_0$). The repeated ANOVA did not report meaningful differences between (conditions) EOL and TW exercise for SLJ ($BF_{10}$ = 0.33, *moderate* in favor of $H_0$), CMJ ($BF_{10}$ = 0.27, *moderate* in favor of $H_0$), or 5 m sprint ($BF_{10}$ = 0.218, *moderate* in favor of $H_0$).

Bayesian post-hoc analysis comparing baseline values and time following EOL was reported for the following parameters: SLJ at 1 min ($BF_{10}$ = 0.165, *moderate* in favor of $H_0$), 3 min ($BF_{10}$ = 7.24, *moderate*, +8%), and 7 min ($BF_{10}$ = 19.5, *strong*, +7%); CMJ at 1 min ($BF_{10}$ = 0.19, *moderate* in favor of $H_0$), 3 min ($BF_{10}$ = 3.25, *moderate*, +9%), and 7 min ($BF_{10}$ = 4.12, *moderate*, +10.5%). Bayesian post-hoc analysis comparing baseline values and time following TW was reported for

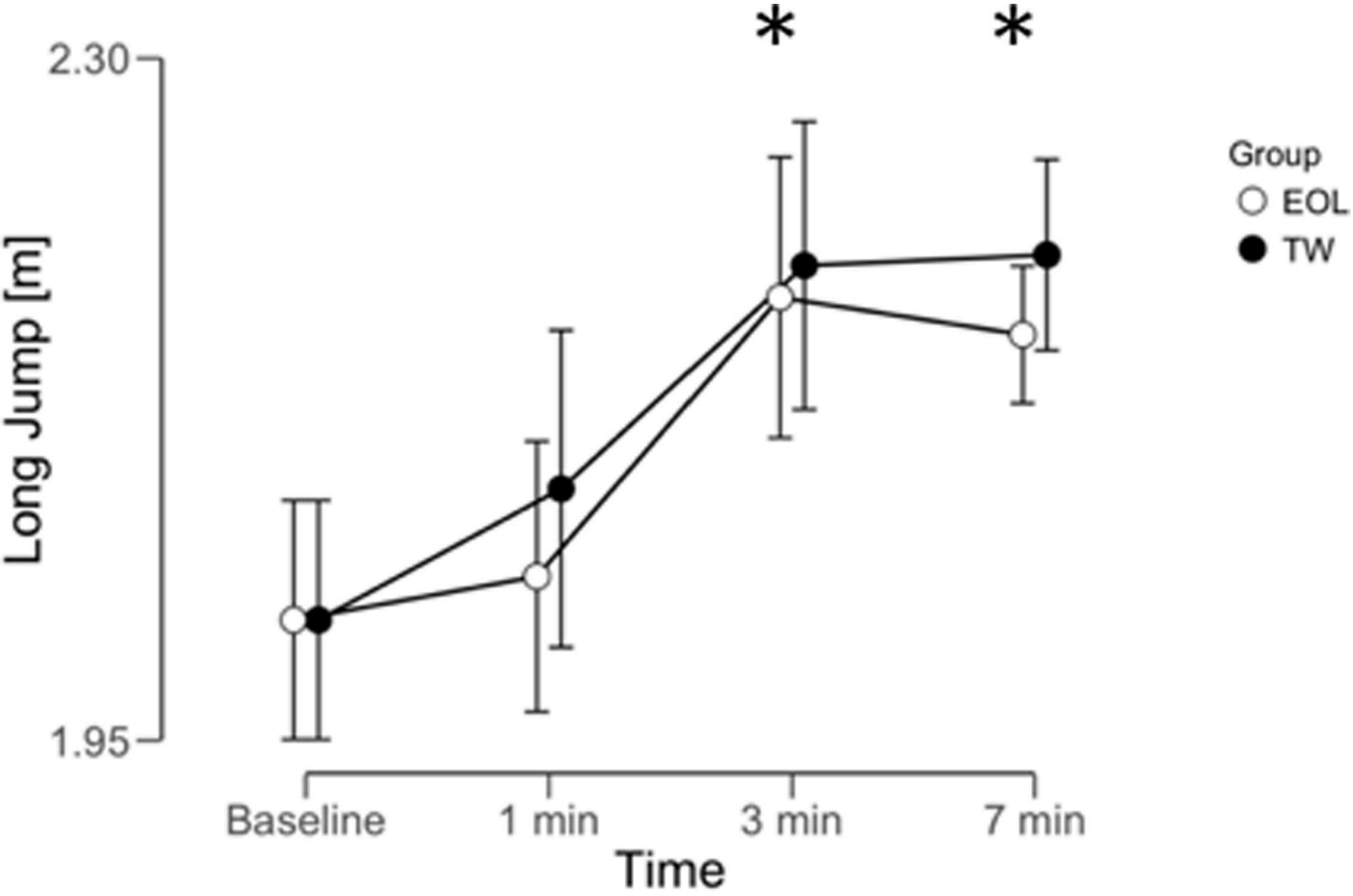

**Fig 2. PAP time window on long jump performance following eccentric overload (EOL) and traditional weightlifting (TW) exercise.** Data reported as mean ± 95% credible interval (n = 10). * = meaningful difference compared to baseline for both protocols.

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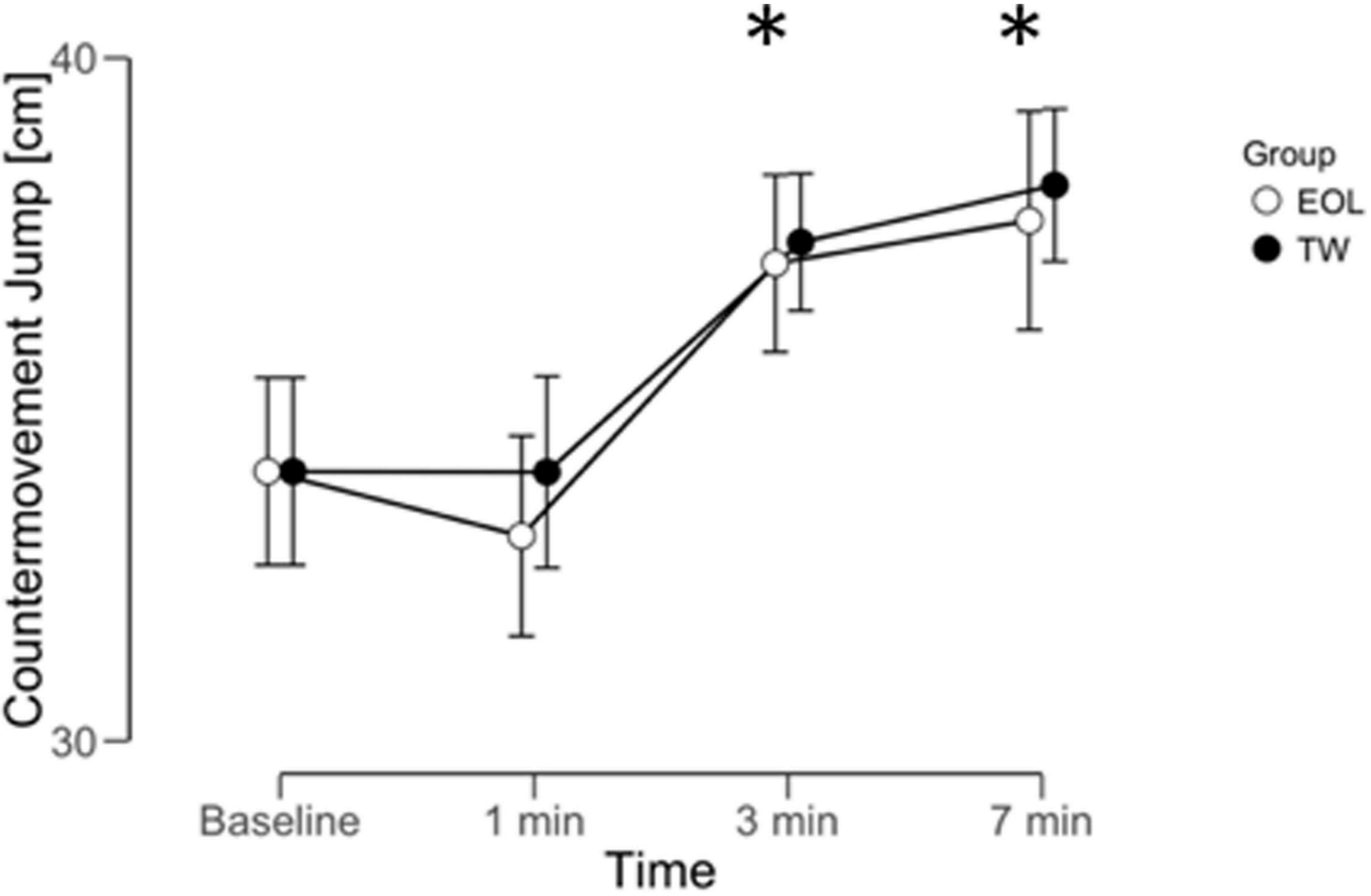

**Fig 3. PAP time window on countermovement jump performance following eccentric overload (EOL) and traditional weightlifting (TW) exercise.** Data reported as mean ± 95% credible interval (n = 10). * = meaningful difference compared to baseline for both protocols.

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the following parameters: SLJ at 1 min ($BF_{10}$ = 0.22, *moderate* in favor of $H_0$), 3 min ($BF_{10}$ = 3.88, *moderate*, +9%), and 7 min ($BF_{10}$ = 12.4, *moderate*, +9%); CMJ at 1 min ($BF_{10}$ = 0.12, *moderate* in favor of $H_0$), 3 min ($BF_{10}$ = 7.42, *moderate*, +9.5%), and 7 min ($BF_{10}$ = 12.4, *strong*, +12%). Post-hoc analysis regarding 5 m sprint was not performed since no time effect was reported.

## Discussion

To the best of the authors' knowledge, this study is the first to investigate the PAP response following EOL and TW exercises on SLJ, CMJ and 5 m sprint tasks. This study compares, also for the first time, PAP magnitude between EOL and TW exercises on functional lower limb tests, matching concentric peak power between the exercises. The present study showed that a meaningful positive PAP response can be observed after 3 min of recovery (and persists until at least 7 min) following both EOL and TW exercises on SLJ and CMJ performance but not on 5 m sprint performance in male amateur athletes. Furthermore, meaningful evidence (in favor of $H_0$) revealed no differences in PAP response for each performance variable analyzed between EOL and TW protocols, therefore both protocols exhibited similar PAP responses. These findings may have an important impact on practitioners' strength training strategies in order to develop PAP and enhance its magnitude and time window.

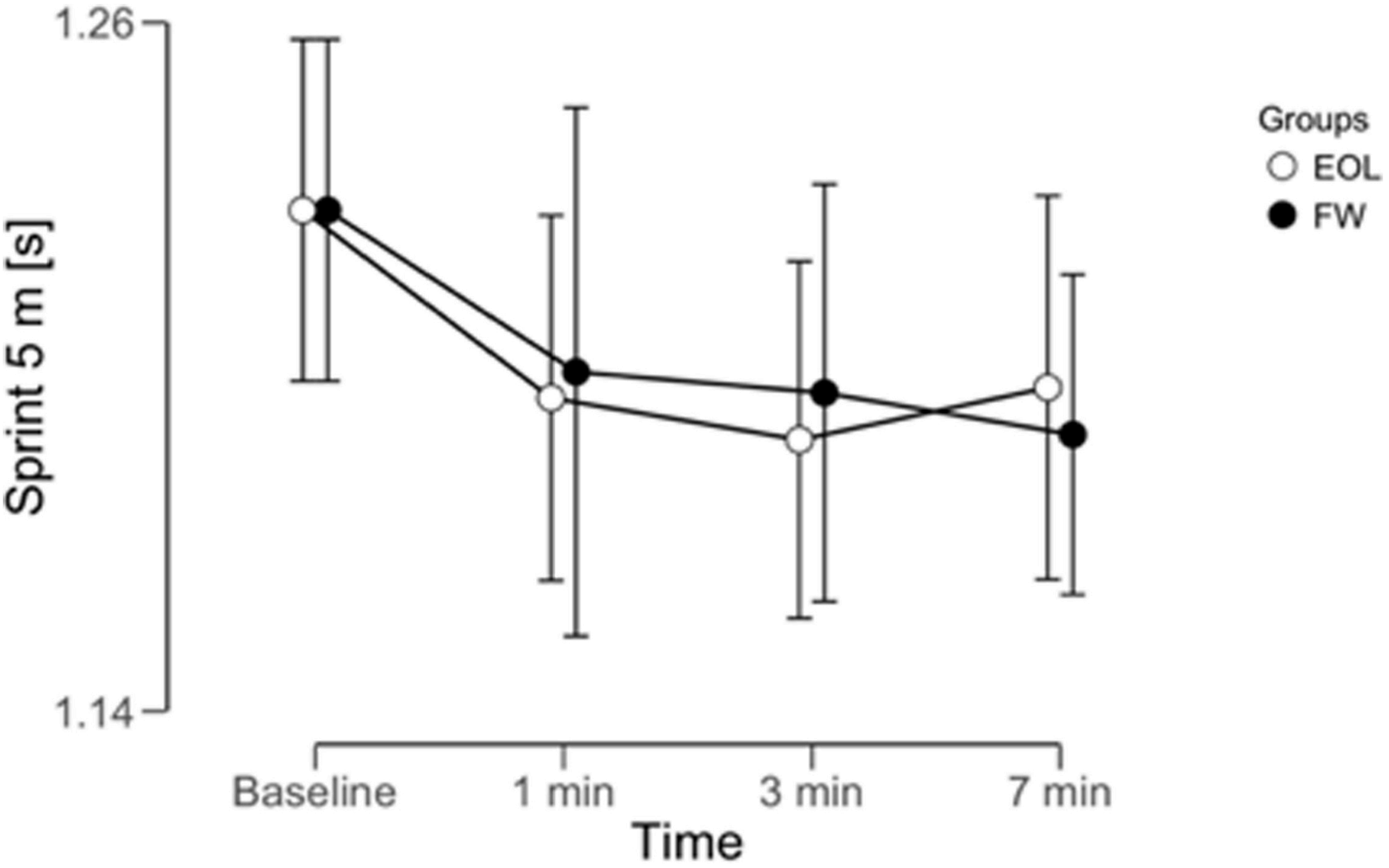

**Fig 4. PAP time window on sprint 5 m performance following eccentric overload (EOL) and traditional weightlifting (TW) exercise.** Data reported as mean ± 95% credible interval (n = 10). * = meaningful difference compared to baseline for both protocols.

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PAP is a physiological phenomenon that can be observed following a pre-load strategy and has previously been identified as a strength–power–potentiation complex [8]. Previous studies reported that PAP effects on CMJ performance (*e.g.* jump height, peak power, and impulse) and short sprinting tasks may be obtained after an EOL exercise [1,7]. Similarly, the literature supports such positive improvements (*e.g.* horizontal and vertical jump performance) following TW exercises [28]. For example, TW back squat, using different intensities (*e.g.* moderate or heavy), may induce a positive PAP response on jumping activities following a recovery period [3]. The current study supports the general knowledge that PAP is observed following a recovery period [4]. Therefore, a passive recovery of around 3 min seems to be sufficient between the pre-load strategy (*e.g.* EOL or TW) and the following sport-specific task (*e.g.* SLJ, CMJ) in order to observe performance benefits. Previous evidence reported that PAP time windows may be altered using different pre-load strategies [8]. However, the current study finds similar PAP time windows between EOL and TW exercises [4,6,7]. Future investigations, however, are needed to better clarify the optimal onset of PAP (*e.g.* lower volume protocols may be beneficial for PAP without stimulating as much acute fatigue) since the current study used 3 sets of 6 repetitions. This study reports that following an acute improvement in sport-specific tasks at 3 min, such positive effects were confirmed at 7 min using both EOL and TW exercises. Such a result is in line with the major body of evidence in the literature reporting an optimal time window between 3 and 10 min [7,29,30]. A recent meta-analysis found that the recovery time affects PAP magnitude, and that the optimal time window should be between 4 to 8 minutes, while a shorter recovery time (*e.g.* 1 min) may reduce the PAP effect on sport specific tasks [8].

The findings reported in the current study support the previous knowledge on performance improvements following a pre-load exercise except for 5 m sprint, for which a PAP effect was not found following either EOL or TW exercise. This result may be attributable to the following observations: 5 m may not be a suitable sprint distance to assess PAP and a longer (*e.g.* 10 or 20 m) sprinting distance could be more suitable (reliability of the sprint test increases with distance) [21]; from a biomechanical perspective short accelerations may be affected by subjects' coordination, which could have impaired the 5 m sprint PAP response obtained with the present protocols; and finally, because both EOL and TW exercises were not biomechanically similar to the sprint, which may have limited the transfer to sprinting capacity. Indeed, the kinetic responses to a pre-load exercise may be related to its specific directional loading nature (*e.g.* vertical loading during a squat exercise) [31]. Therefore, a different exercise such as a barbell hip trust or a single step acceleration using a flywheel may be more effective for acute sprinting improvements due to the more horizontal nature of those exercises relative to the participant.

To the authors' knowledge, this is the first study that compares the PAP effects of an EOL squat with TW squat exercise matching the concentric peak power. Therefore, a comparison between the current study and the literature is not possible. EOL and TW reported no meaningful differences in concentric peak power production, while EOL reported a *very strong* difference in eccentric peak power compared to TW. These results support the validity of the protocol used to match EOL and TW concentric intensities and underline also the EOL induced by flywheel exercise compared to TW. This greater eccentric load is a *peculiaritas* of flywheel exercises, since during the positive (extension) phase of a squat, the subject executes a high velocity movement (generally maximal) while during the negative (flexion) phase of the squat, the subject has to break the load accumulated during the previous phase.[1] Therefore, the principal advantage of EOL is related to an enchained mechanical load that is not possible using TW exercises. Authors supposed that a high eccentric load may have better stimulated higher order motor units (which require the utilization of high load), which may have guaranteed a positive transfer in motor unit recruitment, force, and power production during the following tasks (*e.g.* SLJ and CMJ) [7,32]. Additionally, acute performance improvements in sport-specific tasks may be associated with increased motor unit recruitment, rate coding, and neuromuscular inhibition [7,33]. Despite this strong theoretical rationale, this study found *moderate* effect in favor of $H_0$ for PAP responses between the two pre-load exercises. Therefore, EOL and TW exercises, when matched for concentric peak power, reported equivalent PAP responses on SLJ, CMJ, and 5 m sprint performance. It is noteworthy that there is *moderate* statistical evidence in favor of similarity between the two methods (evidence in favor of $H_0$). The results reported in the current study should be considered innovative since no previous studies have compared the PAP time windows following EOL and TW exercises. Furthermore, they may help strength and conditioning coaches to augment PAP strategies for athletes. Practitioners need to individualize recovery time and PAP onset obtained by EOL and TW exercises in order to enhance benefits from such strategies in competitions and complex training interventions [34]. Future studies on this argument are needed to confirm or contradict the findings of this study.

Existing literature reports that PAP effect magnitudes are related to the pre-load modality adopted. For instance, plyometric exercises seems to be more effective than both moderate and high intensity TW exercises, while maximal isometric contractions do not seem beneficial [8].

However, many factors may affect PAP such as the subject's resistance training background (experienced vs inexperienced), as well as fitness level, where stronger individuals generally exhibit a larger PAP effect than weaker [8]. Moreover, PAP time window and magnitude may be related to the subjects' muscle properties such as percentage of fast fibers [4,35]. Those factors should be further studied to understand the possible PAP differences between EOL and TW. Furthermore, the magnitude of the PAP effect could be different if an experienced (in strength training) cohort was enrolled. Such speculation may be supported by Dello Iacono et al. [31] that showed a PAP response (in acceleration tasks) following both moderate and intensive barbell hip trust exercises but that the effects differed according to the subject's strength level. Authors may speculate that subjects' device-specific resistance training background should be considered when selecting an exercise modality. For example, it is not known whether previous TW experience can be easily transferred to EOL exercise PAP response.

The current study is not without limitation. Firstly, this research has the assumption that PAP is the main explanation for the observed findings of improved performance but there is no explicit measurement of muscular activity and therefore direct evidence that PAP is the only mechanism underpinning such changes. Such limitation should be taken into consideration since the current research did not use a control group, but this design was utilized to reduce intrasession fatigue [7], furthermore because a possible placebo effect associated with the subjects' knowledge of PAP could explain some changes. Secondly, this study compared EOL and TW exercise matching the intensity using the peak concentric power output. However, during the eccentric phase of EOL exercise the peak power was meaningfully greater than the eccentric peak power of TW exercise. Therefore, the total power (concentric and eccentric) generated by subjects was greater during the EOL than the TW squat exercise. Furthermore, practitioners need to consider access to EOL equipment in their daily practice, which could be less common than TW equipment. Lastly, this study enrolled a sample of amateur male athletes, therefore wider generalization cannot be inferred to other samples with different characteristics such as female athletes and professional athletes who may exhibit different PAP time window and magnitude responses [8,36,37].

## Conclusions

The present study suggests that both EOL and TW squat exercises acutely increase SLJ distance and CMJ height but not 5 m sprint performance in male amateur athletes. The onset of the PAP time window was found at 3 min following the protocol and the improvements in sport-specific tasks persisted at 7 min. This study did not find differences between EOL and TW exercises in PAP amplitude. Therefore, both exercise methodologies can be used to acutely stimulate PAP in a similar way before competitions and training sessions. Further research is needed to better clarify the similarities or differences in PAP time window and magnitude between EOL and TW squat exercise.

### Practical applications

Practitioners may use either EOL or TW squat exercises to stimulate a PAP response in athletes. Such acute potentiation has a positive effect on horizontal and vertical jumping performance, however, both protocols seem not to be efficient in improving sprinting acceleration performance. Future studies should explore this topic before drawing final conclusions, as well as clarifying the differences between the protocols. To optimize the PAP effect using EOL and TW pre-load methodologies (3 x 6 repetitions, with concentric peak power outputs of 1097 W and 1030 W, respectively), it is necessary to wait for 3 minutes following pre-load before initiating sport-specific movements; such PAP effects remain at least 7 min after completion of either pre-load strategy. Therefore, practitioners should consider such PAP time windows in sport-specific tasks before competitions or during training sessions (*e.g*. complex training). Furthermore, authors suggest individualizing the PAP protocol on the basis of athletes' training experience, strength level, and morphological characteristics. This may help to optimize PAP as well as minimize acute fatigue and soreness. Authors suggest consideration of pre-load exercise (EOL or TW) on the basis of athletes' previous strength training experience with such protocols.

## Author Contributions

**Conceptualization:** Marco Beato, Alexander E. J. Bigby, Giuseppe Coratella.

**Formal analysis:** Marco Beato.

**Investigation:** Giuseppe Coratella.

**Methodology:** Giuseppe Coratella, Stuart A. McErlain-Naylor.

**Software:** Stuart A. McErlain-Naylor.

**Supervision:** Fabio Y. Nakamura.

**Writing – original draft:** Marco Beato, Alexander E. J. Bigby, Kevin L. De Keijzer, Fabio Y. Nakamura, Stuart A. McErlain-Naylor.

**Writing – review & editing:** Marco Beato, Kevin L. De Keijzer, Giuseppe Coratella, Stuart A. McErlain-Naylor.

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