# Effects of Muscle Action Type With Equal Impulse of Conditioning Activity on Postactivation Potentiation

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## Abstract

Bogdanis, GC, Tsoukos, A, Veligekas, P, Tsolakis, C, and Terzis, G. Effects of muscle action type with equal impulse of conditioning activity on postactivation potentiation. *J Strength Cond Res* 28(9): 2521–2528, 2014—This study investigated the effects of muscle action type during conditioning activity (half-squat) on subsequent vertical jump performance. Fourteen track and field athletes (relative half-squat of 2.3 ± 0.3 times their body weight) completed 4 main trials in a randomized and counterbalanced order 5–7 days apart: (a) concentric (CON) half-squats: 7.5 ± 1.2 repetitions against 90% of 1 repetition maximum (1RM), (b) eccentric (ECC) half-squats: 9.3 ± 1.5 repetitions against 70% of 1RM, and (c) 3 sets of 3-second maximal isometric (ISO) half-squats, (d) a control (CTRL) trial, where subjects rested for 10 minutes. The number of repetitions in CON and ECC was adjusted so that the impulse of the vertical ground reaction force was similar to ISO. Countermovement vertical jump (CMJ) performance was evaluated for 21 minutes after each main trial. Countermovement vertical jump performance in ISO was higher than CTRL from the second to the 10th minute of recovery, whereas CMJ performance in ECC was higher than CTRL from the sixth and 10th minute of recovery. Analysis of the peak individual responses revealed an increase in CMJ performance compared with baseline only in ISO (3.0 ± 1.2%; $p = 0.045$), whereas no significant increases were observed in ECC and CON. Peak CMJ performance for all subjects in ISO and ECC was achieved within 2–10 minutes after the conditioning muscle actions. Isometric were more effective than CON and ECC muscle actions in increasing explosive leg performance when the impulse of the ground reaction force of the conditioning exercise was equated.

**Key Words** complex training, fatigue, countermovement vertical jump, concentric, eccentric, isometric

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*28(9)/2521–2528*

*Journal of Strength and Conditioning Research*
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## Introduction

Complex training is a method that combines a high-load conditioning exercise that stimulates the neuromuscular system, followed by a plyometric exercise of the same muscle groups, in which power output is augmented (12). Both acute and chronic gains in muscle power may be further enhanced by performing an explosive exercise, while the muscle groups involved are in this potentiated state (10,37). Enhancement of muscle power output in the second exercise is termed as postactivation potentiation (PAP) and has been attributed to increased phosphorylation of regulatory myosin light chains, acute changes in the pennation angle of muscle fascicles (11,16), and increased recruitment of motor units (34). However, the conditioning muscle action also causes fatigue, and the interaction between fatigue and PAP determines whether muscle explosive performance will be enhanced in the exercise that follows (23).

Several factors affect the balance between fatigue and PAP, such as volume, intensity and type of the conditioning muscle action, as well as the recovery period between the conditioning and the plyometric exercise (33). Many studies have examined PAP following different types of exercise (13,20,24,33,35,36). The improvement of muscle performance ranged from 1 to 17% (8,9,14,24,25) and was observed 4–12 minutes after the conditioning exercise (9,19). One of the possible sources for this variability may be the type of muscle action during the conditioning exercise because the magnitude of potentiation and muscle fatigue may differ between isometric (ISO), eccentric (ECC), and concentric (CON) exercises. However, only few studies have compared the effects of muscle action type on subsequent performance. Rixon et al. (24) compared the effects of maximal ISO (3 × 3 seconds) and dynamic half-squat exercise (3 repetitions at 90% of 1 repetition maximum [1RM]) on countermovement vertical jump (CMJ) performed 3 minutes after the conditioning exercise. They concluded that the ISO condition evoked greater muscle PAP than the dynamic condition (2.7 vs. 1.7%; $p < 0.01$), only in men. In contrast, Tsolakis et al. (35) found a decrease in CMJ performance 8 and 12 minutes after a 3 × 3-second maximal ISO leg press exercise and no change in CMJ height after plyometric exercise (3 × 5 tuck jumps). In



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the study of Turki et al. (36), only CON muscle actions (3 sets of 3 repetitions with a load of 3RM) evoked an increase in CMJ performance, whereas maximal ISO actions from a squat position (3 × 3 seconds) and plyometric actions (3 × 3 tuck jumps) did not have any effect on subsequent performance (36). The 2 studies that examined the influence of muscle action type on subsequent sprint exercise (20,33) reported the absence of PAP, with large interindividual variations. One possible explanation for those inconsistent results when comparing the different muscle action types may be the different volumes of muscle work, combined with the different timing of performance measurements. This has been noted before (34), but to our knowledge, no study has attempted to equate the volumes of conditioning exercise to reach valid conclusions when comparing different muscle action types. Thus, the purpose of this study was to investigate the effect of CON, ECC, and ISO actions of the lower leg muscles with equated volumes of conditioning exercise on vertical jump performance and to determine the optimum timing of potentiation.

## Methods

### Experimental Approach to the Problem

To evaluate the effects of muscle action type of the conditioning activity (half-squat) on subsequent vertical jump performance, the participants completed 4 main trials. The main trials were conducted 5–7 days apart in a randomized and counterbalanced order and involved ISO, ECC, or CON conditioning actions (half-squat) and a control (CTRL) condition. Conditioning exercise for the 3 different muscle action types (ISO, CON, and ECC) was equalized using the impulse of the vertical ground reaction force. Countermovement vertical jump performance was evaluated at intervals of 2–3 minutes for 21 minutes after each main trial to compare the PAP effect between the 3 muscle action types.

**Table 1.** Physical characteristics and maximal half-squat strength ($n = 14$, mean ± *SD*).*

| | Mean ± *SD* |
|---|---|
| Age (y) | 28.1 ± 6.6 |
| Body mass (kg) | 79.0 ± 7.1 |
| Height (m) | 1.77 ± 0.05 |
| Body fat (%) | 9.1 ± 6.8 |
| Dynamic 1RM half-squat (kg) | 178 ± 25 |
| Concentric 1RM half-squat (kg) | 180 ± 24 |
| Relative dynamic strength ($kg \cdot kg^{-1}$ BM) | 2.26 ± 0.31 |
| Relative concentric half-squat ($kg \cdot kg^{-1}$ BM) | 2.28 ± 0.25 |
| Knee angle dynamic half-squat (°) | 85.1 ± 3.4 |

*BM = body mass; 1RM = 1 repetition maximum.
†$p < 0.01$ from knee angle during the dynamic half-squat.

### Subjects

Fourteen men, track and field national level power athletes, took part in this study (Table 1). Most subjects were decathletes ($n = 6$), jumpers ($n = 4$), sprinters ($n = 2$), and throwers ($n = 2$). As a prerequisite for participation, each subject was able to lift >2 times his body weight in the half-squat (knee angle: 90°). The participants took part in 5–8 training sessions per week and had at least 6 years of weight training experience (average: 12.1 ± 5 years). All athletes were using the half-squat exercise as part of their strength training routines. Subjects were free from musculoskeletal injuries. Written informed consent was obtained from each participant after a thorough explanation of the testing protocol, the possible risks involved, and the right to terminate participation at will. The study was approved by the local institutional review board, and all procedures were in accordance with the Helsinki declaration of 1975, as revised in 1996.

### Procedures

Subjects visited the laboratory on 8 separate occasions and completed 4 preliminary and 4 main sessions. After familiarization and preliminary measurements, the 4 main tests were performed at the same time of the day, 5–7 days apart. Before each main test, subjects were asked to refrain from consuming caffeine or alcohol and were instructed to avoid any kind of intense exercise 24 hours before the experimental conditions (15).

A standardized warm-up included 5 minutes of light jogging on a treadmill (50–60% of predicted maximal heart rate) and 5 minutes of dynamic stretching (36) preceded every preliminary measurement and main trial.

### Familiarization and Preliminary Measurements

In the first preliminary visit, subjects were familiarized with half-squat using different types of muscle action (CON, ECC, and ISO) in a squat rack. Subjects were supervised and instructed for the correct lifting technique by an experienced weightlifting coach (1). Subjects were also familiarized with CMJ (6).

*Anthropometric Measurements.* Body height was measured to the nearest 0.1 cm using a stadiometer (Charder HM-200P Portstad), and body mass was measured to the nearest 0.1 kg (Seca 700; Seca Ltd., United Kingdom). Body fat was estimated from 7 skinfold measurements (18).

*Maximal Dynamic Half-Squat Strength.* Maximal half-squat strength (knee angle: 90°) was assessed in the second preliminary visit according to the procedures outlined by the National Strength and Conditioning Association (1). The determination of 1RM was carried out in a squat rack using a standard Olympic bar and weight plates (Eleiko, Halmstad, Sweden). Ground reaction force was recorded during each trial using a force platform (Applied Measurements Ltd., Reading, United Kingdom), interfaced with a personal computer at a sampling rate of 1,000 Hz. The intraclass correlation coefficient (ICC) for the dynamic half-squat 1RM



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measurement was 0.98 ($p < 0.01$). Knee angle at the lowest point of the movement of the half-squat was measured using a high-speed digital camera (Casio Exilim Pro EX-F1) at 60 frames per second and the Kinovea Video Analysis Software (v. 0.8.15). The ICC for minimum angle measurement during dynamic half-squat was 0.96 ($p < 0.01$).

*Maximal Concentric and Isometric Half-Squat Strength.* The 1RM CON half-squat strength was measured in the third preliminary visit as previously described (1). All lifts were performed in a squat rack with subjects standing on a force platform that recorded vertical ground reaction force. Minimum knee angle was measured as described above, and feet and torso position were kept the same in all half-squat strength tests. In the 1RM CON test, subjects performed only the CON part of the half-squat movement. The initial position of the barbell was set individually using the adjustable barbell stops of the squat rack, so that the subject was at a half-squat position with 90° knee angle. Then the weight was lifted forcefully, and at the end of the movement the barbell was taken by 2 assistants. The ICC for the CON half-squat 1RM measurement was 0.99 ($p < 0.01$). Then, subjects rested for 30 minutes and maximum ISO half-squat strength was measured (knee angle: 90°) after a standardized warm-up. The barbell was loaded with 140% of CON 1RM of each individual and was also stabilized by 2 assistants to avoid any vertical movement. Subjects were instructed to push the barbell as forcefully and as fast as possible for 3 seconds. Three seconds of maximal attempts were performed with 3-minute rest in between, and peak ground reaction force was recorded. The ICC for the peak force measurement during the ISO half-squat 1RM measurement was 0.95 ($p < 0.01$).

*Eccentric Half-Squat Exercise.* The ECC half-squat started with the subjects standing upright with the loaded bar on their shoulders. Then, the knees were bent and the body was allowed to lower under the influence of gravity. The downward (squat) movement was stopped by a sudden ECC action of the knee and hip extensors, so that knee angle was 90° at the lowest point. Subjects were assisted to stop the movement at the desired knee angle by a "beep" sound that was activated when a photocell beam was interrupted by the posterior portion of the thigh when knee angle was just above 90°. The bar was then placed on the adjustable stops of the squat rack and lifted by 2 assistants to the initial position, that is, subjects performed only the ECC part of the movement. Because of the technique requirements of this exercise, subjects were thoroughly familiarized with this movement by performing submaximal ECC half-squats at the end of each preliminary visit.

*Half-Squat Exercise Load During the Conditioning Muscle Actions.* The load for the CON conditioning actions was set at 90% of 1RM according to the findings of several experiments showing that high loads are required to induce PAP (7,22,27). The load for the ECC conditioning actions was determined in a separate pilot study, where peak vertical ground reaction force and the rate of force development (RFD) were measured during ECC half-squats with different loads (from 30 to 90% of the dynamic 1RM in increments of 10%). Both peak force and RFD were maximized at the load of 70% 1RM and remained unchanged at higher loads. Thus, the load of 70% 1RM was used in the ECC condition because it was characterized by high force and RFD, while it could be better tolerated by the participants. The ISO conditioning muscle actions were performed for a total of 9 seconds (3 repetitions, each lasting 3 seconds) with maximal voluntary effort (31).

*Equalization of Exercise Load During the Conditioning Muscle Actions.* During the last preliminary visit, conditioning exercise load for the 3 main trials including different muscle action types (ISO, CON, and ECC) was equalized by measuring the impulse (area under the force curve) of the vertical ground reaction force. After the standardized warm-up, subjects stood on the force platform with the appropriate feet, torso, and knee position and performed, in random order, 3 blocks of exercise (ISO, CON, and ECC muscle actions):

- Three single, maximum-effort, CON half-squat attempts against a load of 90% of the CON 1RM, separated by 1-minute rest
- Three single ECC half-squat attempts against a load of 70% of 1RM, separated by 1-minute rest
- Three maximum ISO half-squat actions, each lasting 3 seconds, separated by 1-minute rest.

To ensure complete recovery, each block of exercise (ISO, CON, and ECC muscle actions) was separated by 30 minutes of rest. A standardized warm-up preceded each set of measurements. Total impulse of the vertical component of the ground reaction force (including body weight) was measured for each muscle action type and was used for the equalization of the 3 exercise conditions.

The summed impulse during the 3 × 3-second maximum ISO actions, measured in the last preliminary visit, was used to standardize the conditioning exercise for the other 2 muscle action types. Briefly, for each subject, the total impulse of the 3 × 3-second maximum ISO actions was divided by the impulse of 1 CON repetition to determine the number of repetitions required to generate the same impulse in the CON as in the ISO trial. Similarly, the number of repetitions for the ECC trial was determined by dividing the impulse of 1 ECC repetition measured in the last preliminary visit by the total ISO impulse. Table 2 shows the average number of repetitions performed in the CON and ECC main trials, so that total impulse was similar to the ISO main trial.

**Main Trials**

The main trials were conducted 5–7 days apart in a randomized and counterbalanced order and involved ISO, ECC, or CON conditioning actions (half-squat) and a CTRL condition. In all main trials, 1 minute after the end of the standardized warm-up, subjects performed 3 CMJs separated by 30 seconds of rest on



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**TABLE 2.** Characteristics of exercise during the 3 types of conditioning contractions ($n = 14$, mean ± *SD*).*

| | ECC | CON | ISO |
|---|---|---|---|
| Weight of the loaded bar (kg) | 124 ± 18† | 161 ± 19 | |
| Number of repetitions | 9.3 ± 1.5† | 7.5 ± 1.2 | 3.0 ± 0 |
| Total volume lifted (kg × repetitions) | 1,124 ± 137 | 1,175 ± 149 | |
| Total duration (s) | 10.3 ± 1.1‡ | 9.3 ± 1.6 | 9.2 ± 0.6 |
| Total impulse (N·s) | 19,360 ± 3,434 | 19,862 ± 4,045 | 19,737 ± 2,779 |
| Average force (N) | 1,886 ± 252†‡ | 2,149 ± 292 | 2,142 ± 234 |
| Peak force (N) | 2,788 ± 263†‡ | 3,108 ± 316‡ | 2,522 ± 333 |
| Knee angle at lowest point (°) | 88.0 ± 3.6 | 90.0 ± 3.5 | 90.2 ± 3.2 |

*ECC = eccentric; CON = concentric; ISO = isometric contractions; total volume lifted = the weight lifted multiplied by the number of repetitions (reps).
†$p < 0.01$ from CON.
‡$p < 0.01$ from ISO.

a force platform, and the best was kept as the baseline value. The ICC for the CMJ measurement was 0.98 ($p < 0.01$).

*Specific Warm-up*. After the baseline CMJ measurements, subjects rested for 3 minutes and then performed a specific weightlifting warm-up routine depending on the condition. In the CON trial, the specific warm-up included 3 repetitions at 50%, 2 repetitions at 70%, and 1 repetition at 80% of the CON 1RM, separated by 1-minute rest. In the ECC trial, the specific warm-up included 3 repetitions at 40%, 2 repetitions at 50%, and 2 repetitions at 60% of the dynamic 1RM, separated by 1-minute rest. In the ISO trial, the specific warm-up included 3-second ISO actions from a half-squat position, separated by 1 minute of rest, at approximately 50, 75, and 90% of the individual maximum voluntary ISO strength. After 3 minutes of rest, subjects performed the 3 types of conditioning muscle actions or the CTRL trial.

*Experimental Trials*. In the ISO trial, subjects performed 3 sets of 3-second maximal ISO actions from a half-squat position

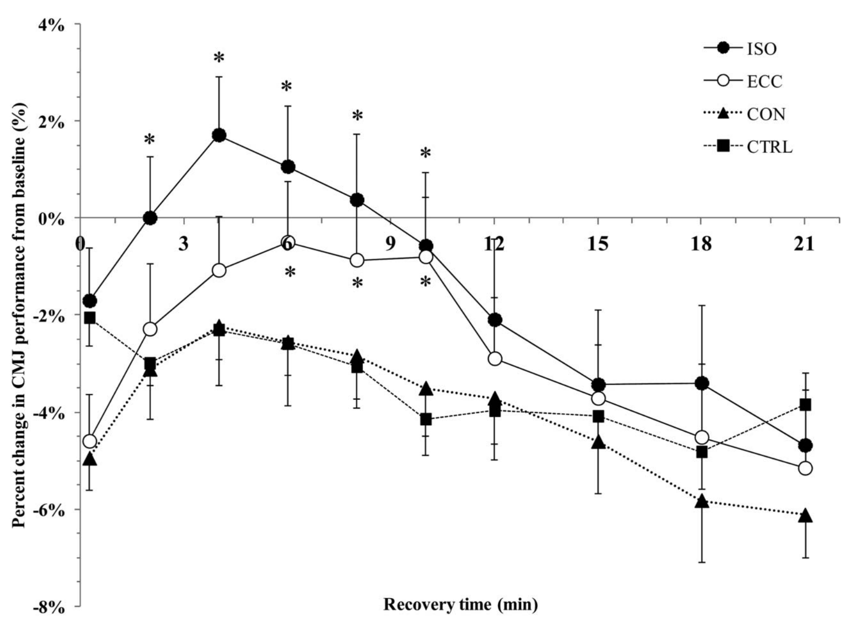


**Figure 1.** Time course of percent changes in CMJ performance compared with baseline values, following the ISO, CON, ECC, and CTRL conditions. Data are expressed as mean ± *SE*. *$p < 0.01$ from the control condition. CMJ = countermovement vertical jump; ISO = isometric; CON = concentric; ECC = eccentric; CTRL = control.



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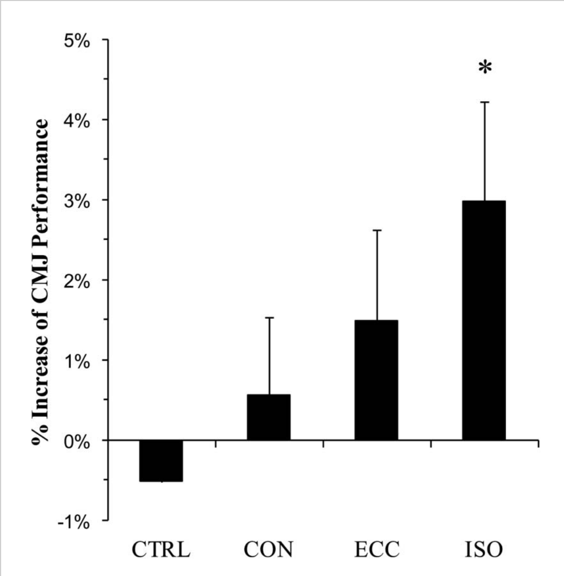


**Figure 2.** Relative increase of CMJ performance calculated from the peak individual responses (peak individual CMJ performance during recovery compared with the baseline value). *$p = 0.045$ significant increase from the corresponding baseline value. CMJ = countermovement vertical jump.

with 1-minute rest between each set. Previous studies have shown that similar ISO exercise protocols induce PAP (20,24). In the CON and ECC conditions, subjects performed an individually predetermined number of single repetitions with maximal effort, so as to match the total impulse generated during the ISO condition.

The characteristics of the exercise during the ECC, CON, and ISO trials are shown in Table 2. The load was set at 90% of the individual CON 1RM for the CON condition and at 70% of the dynamic 1RM for the ECC condition. One minute of rest was allowed between all single repetitions. As described above, subjects performed only the CON part of the half-squat in the CON condition and only the ECC part of the half-squat in the ECC condition. In the CTRL condition, subjects performed only the standardized warm-up and the baseline CMJ measurements and then rested for 5 minutes. In all the 4 conditions, CMJ was measured after the conditioning activity (or 10 minutes of rest after the baseline CMJ measurement in the CTRL condition) at the following time points: 15 seconds, 2, 4, 6, 8, 10, 12, 15, 18, and 21 minutes.

### Statistical Analyses

All statistical analyses were performed using the STATISTICA v.8.0 software (StatSoft, Inc., Tulsa, OK, USA). Data are presented as mean and *SD*. A 2-way repeated-measures analysis of variance (ANOVA) (type of conditioning muscle action × recovery time) was used to examine the effects of the type of conditioning muscle action and recovery time on CMJ jump performance. Tukey's post hoc tests were performed when a significant main effect or interaction was obtained ($p \leq 0.05$) to locate differences between means. Effect size for main effects and interaction was estimated by calculating partial eta squared ($\eta^2$) values. Effect size for pairwise comparisons was obtained by calculating Cohen's *d*. Effect sizes were classified as small (0.2), medium (0.5), and large (0.8). Test-retest reliability for all the dependent variables measured in this investigation was determined in separate experiments by calculating the ICC using a 2-way mixed model. Statistical significance was accepted at $p \leq 0.05$.

## Results

The absolute and relative to body mass values of maximal (1RM) dynamic and CON half-squat strength are shown in Table 1. The characteristics of exercise during the 3 types of conditioning muscle actions are presented in Table 2. Total impulse was similar in the 3 conditions ($p = 0.86$, $\eta^2 = 0.01$), confirming the successful equalization of exercise load. However, the same impulse was achieved with a significantly greater number of repetitions in ECC compared with the CON condition. Consequently, average force was lower in ECC compared with both CON and ISO conditions ($p = 0.0001$, $\eta^2 = 0.56$). In contrast, total volume lifted, calculated with the conventional way (i.e., weight lifted multiplied by the number of repetitions), was identical in the ECC and CON conditions. No statistically significant decrease in total impulse was observed from the first to the last repetition in all conditions: (CON: 2,726 ± 674 vs. 2,619 ± 700 N·s [$p = 0.12$, $d = 0.16$]; ECC: 2,174 ± 500 vs. 2,091 ± 510 N·s [$p = 0.29$, $d = 0.17$]; ISO: 6,531 ± 1,284 vs. 6,632 ± 891 N·s [$p = 0.77$, $d = 0.10$], first vs. last repetition, respectively).

Peak force differed between all conditions ($p = 0.0001$, $\eta^2 = 0.84$) with the highest value observed in the CON condition and the lowest in the ISO condition (Table 2).

The time course of percent changes in CMJ performance relative to the baseline values is presented in Figure 1. The 2-way ANOVA revealed a significant main effect for condition ($p = 0.05$, $\eta^2 = 0.18$), time ($p = 0.0001$, $\eta^2 = 0.59$), and a condition × time interaction ($p = 0.004$, $\eta^2 = 0.13$). The post hoc test for the main effect of condition showed that CMJ performance in ISO was greater than CTRL ($p = 0.043$). The post hoc test for the condition × time interaction showed that CMJ performance in the ISO condition was higher than CTRL from the second to the 10th minute of recovery, whereas in the ECC condition CMJ performance was higher than CTRL from the sixth to the 10th minute of recovery (Figure 1). It should be noted that CMJ performance in all experimental conditions (CON, ECC, and ISO) was initially decreased and then recovered partially for the first 8–10 minutes, surpassing the baseline values only in the ISO condition (Figure 1). After the 10-minute time point, CMJ performance declined in all conditions (Figure 1).

Because of the interindividual differences in the time course of CMJ performance changes after a conditioning muscle action, the peak individual responses were also calculated. This



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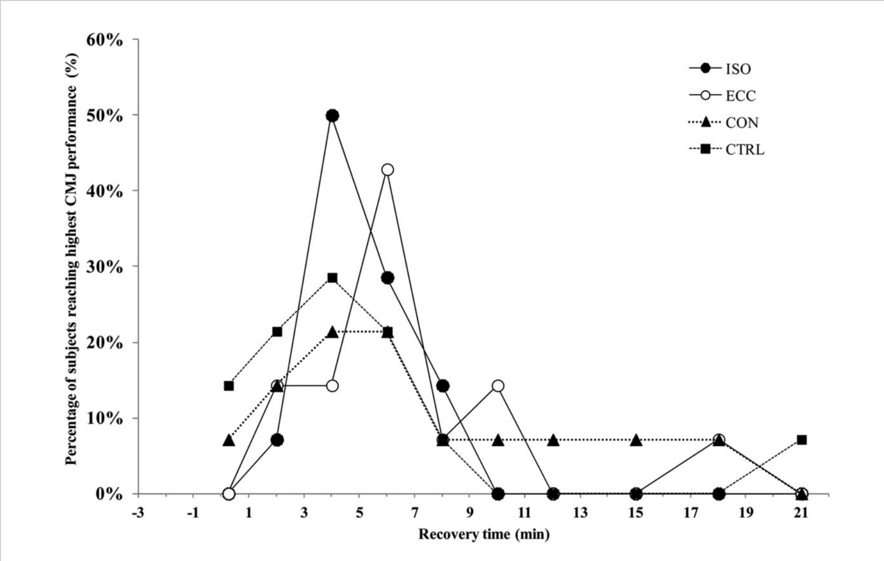


**Figure 3.** Individual times when peak CMJ performance was achieved for each subject. The vertical axis shows the percentage of subjects whose performance peaked at each time point in each condition. CMJ = countermovement vertical jump.

was performed by taking the best CMJ performance of each individual during recovery and expressing it relative to the corresponding baseline. Figure 2 shows the peak individual responses for each condition. A significant increase relative to baseline was seen only in the ISO condition (by 3.0 ± 1.2%; $p = 0.045$), whereas the increases observed in the other 2 conditions (ECC and CON) were smaller and not significant.

The time point where each of the subjects achieved peak CMJ performance is shown in Figure 3, where the percentage of subjects peaking at each time point is presented. From this graph, it is evident that peak CMJ performance for all (100%) the subjects in the ISO condition was achieved between the second and eighth minute of recovery, with half of the subjects (50%) peaking on the fourth minute (Figure 3). Similarly, the peak CMJ performance for the 93% of the subjects in the ECC condition was achieved between the second and 10th minute of recovery, with most subjects (43%) peaking on the sixth minute (Figure 3). It is noteworthy that only a very limited number of subjects (1 or 2 in each condition) achieved their peak performance beyond the sixth minute of recovery.

## Discussion

The main finding of this study was that ISO actions were more effective than CON and ECC muscle actions for inducing PAP, when the impulse of ground reaction force was equated between conditions. The PAP effect of the ISO actions was observed not only when CMJ performance was compared with the CTRL condition but was also greater when the best CMJ performance of each subject was compared with the baseline value (+3.0 ± 1.2%). Furthermore, CMJ performance after ECC muscle actions was greater compared with the CTRL condition at 3 time points (6, 8, and 10 minutes of recovery), but failed to reach significance when compared with the corresponding baseline value.

To our knowledge, this is the first study where conditioning exercise was equated, in an attempt to examine the effects of muscle action type on PAP. The equalization of conditioning exercise was performed using an important functional parameter of exercise load, that is, impulse of ground reaction force. This allowed quantification of the ISO exercise load, so that equal loading could be applied during the 3 exercise conditions (ISO, CON, and ECC). The results of this study confirmed previous findings of Esformes et al. (13) who compared ISO, ECC, CON, and dynamic conditioning muscle actions and found that only a 7-second ISO action increased bench press throw peak power by a similar degree as in our study (2.8%; $p = 0.038$). Similarly, Rixon et al. (24) reported that an ISO protocol similar to that used in this study (3 sets of 3 seconds with 2-minute rest) improved CMJ performance 3 minutes into recovery by 2.9%, but this was observed only in men and not in women. In that study, a set of 3 dynamic half-squats at 90% of 1RM failed to induce PAP. This was explained by the lower metabolic cost of ISO actions resulting in less low-frequency fatigue (24). The authors assumed that the heavy load during the dynamic half-squats (90% of 1RM) led to a progressively slower movement that increased "time under tension" and put the squatter at a biomechanical disadvantage which led to low-frequency fatigue.

In this study, the parameter of "time under tension" (i.e., impulse of force) was measured and was equal in all experimental conditions. If the metabolic cost in ISO was lower compared with the CON and ECC conditions, this may have led to less metabolic disturbances and consequently less fatigue in the ISO compared with the other 2 conditions. Previous studies in human muscle in vivo and rat muscle in situ (3,26) showed that the ratio of the high energy phosphates consumption to the force-time integral was much higher in dynamic compared with ISO actions. This means that ISO are more efficient than CON and ECC muscle actions, per unit of external force. Because muscle performance after a conditioning muscle action depends on the balance between PAP and fatigue (34), the possibly lower metabolic cost in ISO compared with ECC and CON may be related with lower fatigue and thus partially explain the



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greater CMJ performance after ISO actions. Furthermore, ECC condition induced a greater PAP than CON condition. This result may also be related with the greater efficiency of lengthening muscle actions because the metabolic cost is 50–70%, compared with CON actions (3,26), resulting in lower fatigue. According to this hypothesis, the depression of CMJ performance during the recovery period after the CON condition (Figure 1) may be explained by the prevalence of fatigue over PAP, as suggested in previous studies (19). Interestingly, peak force was lower in ISO and higher in CON, despite the same average force (Table 2), supporting the possibility of greater fatigue in the CON and lower fatigue in the ISO condition.

One interesting finding of this study was that CMJ performance was improved compared with the baseline value only in the ISO condition (Figure 1). In the CON condition, CMJ performance failed to reach baseline, although it demonstrated an initial decrease (acute fatigue), followed by a temporary increase, until it dropped again after about 10 minutes of recovery (Figure 1). The failure of CMJ performance to increase above baseline in CON may be explained by the greater fatigue in this condition (34). The number of repetitions performed in the CON condition (7.5 ± 1.2; Table 2) is twice as high compared with what is usually used in PAP protocols (i.e., 3 repetitions at 90% of 1RM (4,8,9,13,36)). This was a result of our equalization procedure, so that the force-time integral was the same in the CON as in the ISO condition. One conclusion of practical importance that may be drawn from our results is that power-trained athletes, such as the subjects in this study, should avoid using such high volumes of load during CON protocols aiming to cause PAP.

The explanation that a high total volume of preload may result in an abolished PAP response has also been put forward in previous studies. For example, Ruben et al. (25) concluded that a total volume of back squat of 1,109 ± 234 kg, that was similar to that used in our study (Table 2), may be responsible for the lack of improvement of horizontal jumping performance. In contrast, studies using only 3 repetitions at about 90% of 1RM (total volume of about 400–450 kg) have found increases in CMJ performance (9,36). The possibility that excessive volume of conditioning exercise may prevent performance increase during the recovery interval may also explain the results in the ECC condition, where total volume was over 1,100 kg (Table 2; Figure 1). Thus, the attempt to equate the load to compare the effects of muscle action type on PAP by using muscle action duration (2,13) or the force-time integral (present study) may not ensure an equal "exercise intervention." Because of the different metabolic cost of the 3 muscle action types (3,26), it is suggested that future studies should attempt to equate this parameter (i.e., metabolic cost) to compare the effects of muscle action type on PAP. The possible role of metabolic cost on PAP may be connected with the main mechanism of PAP, that is, phosphorylation of regulatory myosin light chains in the level of muscle (17,34).

Another mechanism that may induce PAP is an increased recruitment of higher order motor units through an increase in postsynaptic potentials (21). This would be measured as an increased electromyographic (EMG) activity in the muscle compared with the preconditioning level. One limitation of this study was that we could not measure EMG during the CMJ. However, previous studies suggest that EMG activity may not change following similar potentiation protocols (13), and thus the peripheral mechanisms (i.e., myosin light chain phosphorylation) may be prevalent.

An almost linear reduction in CMJ performance was observed after 10 minutes of recovery in all conditions (Figure 1). This linear decrease in CMJ performance, that occurred throughout the 21-minute recovery period in the CTRL condition, may be explained by a progressive decrease in muscle temperature. The type of warm-up used in this study may increase muscle temperature by almost 2° C (29). Previous studies reported that an increase of muscle temperature by 1° C increases CMJ performance 3.5–4% in normal environmental conditions (5,30). Thus, part of the expected increase in performance after the conditioning activity in all conditions may be explained by increased muscle temperature. During the initial stages of the recovery period, CMJ performance is more affected by the different conditions (i.e., ECC, ISO, and CON). However, in the later stages of recovery muscle, temperature may play a more important role, explaining the similar rate of decline of CMJ performance in all conditions after the 10th minute of recovery.

One key parameter when examining the potentiating effect of different muscle action types on performance is that there is the individuality of responses. This has been highlighted in several studies where instead of taking the mean value of CMJ performance at each time point the best performance of each individual, irrespective of time, was used to calculate the relative improvement (4). This calculation resulted in 2–3% greater improvements in performance compared with taking the mean at each time point (9). In this study, 50% of the subjects attained their peak performance on the fourth minute of recovery in the ISO condition. However, performance in the remaining 50% peaked at time points ranging from 2 to 8 minutes. Therefore, this different timing of peak performance after a conditioning muscle action should be taken into account.

## Practical Applications

This study has practical implications for power-trained athletes. First, a 3 × 3-second series of maximal ISO actions can be used to enhance muscle power and vertical jump performance of the lower limbs by about 3%. To optimize this effect, the conditioning muscle action should be performed 4–6 minutes before the explosive activity, but the exact timing of peak performance has to be individualized. A series of ECC or CON muscle actions was found to decrease, rather than increase, the explosive performance when the volume of exercise was 9 or 8 repetitions at 70



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and 90% of 1RM, respectively. Therefore, such high exercise volumes of CON and ECC exercises should be avoided, even in strength-trained athletes, if the aim is to acutely enhance performance. Strength and conditioning coaches should use maximum ISO muscle actions to evoke PAP during complex training. Because of the individuality of the time course of potentiation, coaches are advised to use a trial and error (28) method to identify the optimum time of each athlete.

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