The Effects of Eccentric Conditioning Stimuli on Subsequent Counter-Movement Jump Performance

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Abstract

Ong, JH, Lim, J, Chong, E, and Tan, F. The effects of eccentric conditioning stimuli on subsequent counter-movement jump performance. *J Strength Cond Res* 30(3): 747–754, 2016—The eccentric phase in a stretch-shortening cycle is an important determinant of subsequent concentric performance, but there is little information on high-intensity eccentric preconditioning. The purpose of this study was to determine the effects of varying degrees of eccentric conditioning stimuli on subsequent counter-movement jump (CMJ) performance. Fourteen participants (age, 28.5 ± 5.0 years; height, 172.7 ± 6.7 cm; body mass, 74.3 ± 11.9 kg) performed CMJ trials on 3 separate test sessions at least 96 hours apart in a crossover randomized counterbalanced study. Peak power (P_{peak}) and vertical displacement (D_{max}) were measured before and at 3, 6, 9, and 12 minutes (T3–12) postcontrol (0RM), 105% (105RM), and 125% (125RM) 1RM eccentric hip sled. The differences in vertical jump performance parameters between 0RM and eccentric preloading conditions (105RM and 125RM) and the differences within condition between control time point and posteccentric load time course T3, T6, T9, and T12 were analyzed for statistical significance via unequal variance *t* statistic. Statistical significance was set at $p \leq 0.05$. Significantly higher P_{peak}, compared with 0RM (4143 ± 754 W) was seen at T3 and T6 in both 105RM (4305 ± 876 and 4237 ± 842 W) and 125RM (4314 ± 848 and 4264 ± 768 W). Compared with 0RM (42.2 ± 7.8 cm), corresponding D_{max}, was also significantly improved at T3 in both 105RM (44.5 ± 7.3 cm) and 125RM (44.3 ± 8.3 cm) and at T6 in 105RM (44.7 ± 7.7 cm). Compared with baseline (43.2 ± 7.2 cm), there was significantly higher D_{max} at T3 and T6 in 105RM. In conclusion, high-intensity preconditioning eccentric contraction at 105 and 125% 1RM was effective in improving CMJ power and height at 3 and 6 minutes after loading. Thus, power athletes and coaches can consider the application of eccentric preconditioning in warm-up routines.

Key Words postactivation potentiation, complex training, plyometrics, stretch-shortening cycle, warm-up

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Introduction

In most human activities, concentric movement toward the intended direction is preceded by an eccentric movement in the opposite direction. The eccentric–concentric coupling is termed a stretch-shortening cycle (SSC). In a vertical jump, the SSC of the lower limb musculature contributes to greater jump heights when compared with non-SSC jumps (27). Therefore, plyometric activities involving the SSC use varying intensities of counter-movement jumps (CMJ), ranging from simple jumps in place to the accentuated eccentric loading (AEL) of drop jumps (1), to train athletes.

Complex training is a method that combines high-load conditioning exercise that stimulates the neuromuscular system, followed by a plyometric exercise involving the same muscle groups in which power output is augmented (11). This enhancement of performance is termed postactivation potentiation (PAP), which is defined as a phenomenon in which muscular performance is enhanced acutely after an activity executed at relatively high intensity (28). Lowery et al. (28) showed, in a volume-controlled PAP study, that moderate-to-high intensity loading at 70 and 93% concentric one repetition maximum (1RM) through the entire eccentric–concentric squat cycle leads to better jump performance; effects of which peaked at 4 minutes and returned to baseline by 8 minutes. Other studies also demonstrated positive effects of PAP on lower limb kinematics and kinetics in jumping (26) and sprinting (29). Previous studies also focused mainly on dynamic (eccentric–concentric) and isometric loading; thus, stimulus was limited to below 1RM, even for activities such as CMJs in which the eccentric component is important (6,25).

Eccentric contractions have long been known from early studies to produce greater amounts of torque and force compared with concentric and isometric contractions. In a study comparing upper body concentric, eccentric, and isometric strength, Doss and Karpovich (10) showed that elbow flexors eccentric contractions produced 40 and 14% more force than concentric and isometric contractions, respectively. Rodgers and Berger (32) confirmed that the same muscle group produces up to 80% more torque eccentrically than concentrically. Therefore, eccentric preconditioning appears to require a load that is higher than the concentric 1RM during the eccentric phase.

The eccentric stretch or counter-movement component of a SSC is central to the observed higher jump variables achieved in such jumps (3). Sheppard et al. (34) studied lower-body performance in elite-level volleyball athletes measuring CMJ performance using block jumps with and without AEL. Participants were tested for jump performance with an additional 20-kg load during the eccentric phase of CMJ in the accentuated eccentric block jump trials. Results showed significant kinetic and kinematic enhancements to vertical jump performance. Similar improvements have also been noted in upper-limb strength, comparing accentuated eccentric bench presses with equated eccentric–concentric bench presses (9) and for upper-limb power in bench throws under similar test conditions (36). Overloading the eccentric portion of a movement seems to enhance subsequent plyometric performance. It is, however, not possible to replicate AEL-induced performance enhancements during actual competition conditions as eccentric phase of SSC in plyometric movements is performed with only body weight.

To the authors' knowledge, there are no studies comparing eccentric PAP using loads above 1RM, it is thus important to investigate the effects of higher intensity eccentric preconditioning on CMJ performance, to bridge the gap in the understanding of the effects of eccentric PAP on subsequent SSC dynamics. Therefore, the purpose of this study was to determine the effects of different intensities of eccentric loading on subsequent CMJ performance through a time course. It was hypothesized that eccentric preconditioning at intensities above 1RM would lead to improved subsequent CMJ performance.

Methods

Experimental Approach to Problem

The aim of the present study was to investigate the effects of 2 eccentric conditioning loads (105RM and 125RM) on subsequent CMJ performance (peak power and maximal vertical displacement), through a time course (3-minute intervals at 3, 6, 9, and 12 minutes) after eccentric preload. The study will follow a within-subject crossover design where repeated measures will be made for each participant under various eccentric loading conditions. The testing order was randomized and counterbalanced.

Subjects

Fourteen men aged 19 to 35 years (mean ± standard deviation [*SD*]: age, 28.5 ± 5.0 years; height, 172.7 ± 6.7 cm; body mass, 74.3 ± 11.9 kg) with hip sled 1RM of 304.6 ± 52.9 kg participated in this study on a voluntary basis, subsequent to a health screening questionnaire and full written informed consent. Ethics approval from the Singapore Sports Institute (SSI) Institutional Review Board was obtained before the commencement of study, which was performed in accordance to the Declaration of Helsinki. Data collection was conducted at the laboratory facility at the SSI.

All participants were physically healthy and free from current or recent musculoskeletal injuries. They were also recreationally active with at least 12 months of resistance training including that of lower body. The test sessions were carried out at the same time of the day (±1 hour), and participants were also to attend each session attired in the same comfortable nonrestrictive sports clothing and footwear during all test sessions. During the course of the study, the participants were informed to maintain their usual physical activities, sport training, and diet.

Procedures

The study protocol included the completion of a familiarization session (CMJ practice and technique guidance) during which the 1RM for hip sled is determined and 3 testing sessions over a 3-week period. Participants initially visited the laboratory to be familiarized with the experimental protocol, and their height and body mass were also taken. Height was measured to the nearest 0.1 cm using a stadiometer (Holtain Limited, Crosswell, United Kingdom) and body mass was measured to the nearest 0.01 kg using a calibrated electronic scale (Mettler, Toledo, OH, USA). Subsequently, CMJ technique was thoroughly practiced, familiarized, and standardized for all participants at submaximal and maximal effort levels after 5 minutes of generic cycling warm-up at 50 W on a cycle ergometer (Lode Excalibur Sport, Groningen, Netherlands).

Each participant's 1RM for the hip sled (Calgym, Caloundra, Australia; Figure 1.) exercise was then determined. 1RM is defined as the maximum load that can be lifted with proper exercise form and an attempt is deemed successful when the

Figure 1. Hip sled.

hips and knees flex until the thighs are parallel to the foot platform. This is with reference to exercise technique guidelines from the National Strength and Conditioning Association (1). The 1RM testing began with 3 warm-up sets (5–10 reps, 3–5 reps, and 2–3 reps). Three to five trials were typically required to establish the 1RM, and the loading was increased (10–20%) until only one successful repetition was performed. Participants were given 2 minutes of rest between higher repetition trials and a 4-min interval for 1RM trials. In the event of a failed 1RM trial, the weight was decreased until a successful attempt was completed.

The hip sled exercise was used to focus only on overloading the lower-body musculature and deemed a safer and less technically demanding method to administer high eccentric loads as compared with the traditional back squat. After the 1RM testing, the participants then underwent a familiarization and practiced eccentric loading on the hip sled machine at 105 and 125% of 1RM. The technique was standardized, starting at a lower limb extended position with the hip sled machine loaded with selected weight plates and descending on timed cue over 3 seconds to the flexed position.

After the first visit, participants returned to the laboratory on 3 separate occasions at least 96 hours apart for the testing sessions to allow for washout and recovery from any delayed onset muscle soreness from eccentric loading (7). The 3 testing sessions involved a control session (0RM) with no eccentric loading and with eccentric loads at 105% (105RM) and 125% (125RM) of 1RM. The order in which the testing sessions were done was randomized and counterbalanced. The eccentric load for the present study is selected based on prior studies on eccentric exercise, in which loads ranging from 100 to 130% 1RM for investigating bench press performance (9), elbow flexors and extensors (5), knee extensors (14), and musculoskeletal adaptations to eccentric loading (36) have been used.

At the start of each session, participants completed a standardized generic cycling warm-up at 50 W on the cycle ergometer for 5 minutes, followed by dynamic exercise-specific warm-ups with 3 submaximal CMJs with 2 minutes of seated rest allowed at the end of the warm-up. The participants then performed 3 CMJs which served as the control or baseline for the test session (pre). The CMJ trial was performed with the participants' self-determined optimal depth and with hands on the hips, with the aim of jumping as high as possible. For 0RM, no eccentric preload was imposed, and the participants were then allowed 10 minutes of control rest period after the control CMJ. The 10-minute rest period was imposed to standardize the timeline across the eccentric loading protocols (2-minute rest period + 8 minutes of activities). The 8-minute activity window included a warm-up set of eccentric hip sled at 50% load (6 reps @ 5 seconds), followed by a 3-min rest, the main set at 105%/125% load (6 reps @ 5 seconds) and finished with a 3-min rest. This was followed by 4 blocks of CMJ trials at 3-min intervals, with seated rest through the time course. In 105RM and 125RM, eccentric preload was imposed at 105% 1RM × 6 repetitions and 125% 1RM × 5 repetitions, respectively; this was preceded by eccentric loading warm-ups at 50% of working load at working number of repetitions. The eccentric loading volume (load × repetitions) was deliberately controlled for both 105RM and 125RM to avoid any effect confounded by exercise volume. This was followed by 4 blocks of CMJ trials at 3-min intervals at 3 (T3), 6 (T6), 9 (T9), and 12 (T12) min after eccentric preload, with seated rest through the time course. Goveau et al. (16) showed in a meta-analysis that an 8- to 12-minute rest interval after PAP produced the best performance enhancement; whereas Wilson et al. (39) found that the optimal rest period was 7–10 minutes. Individual studies investigating optimal recovery periods have shown results with optimal performance at 4–8 minutes (25) and 5–10 minutes (23) in professional athletes and recreational individuals. A schematic diagram of the experimental procedures and timeline is presented in Figure 2.

Equipment and Measurements

The hip sled machine was used for 1RM testing and eccentric loading. It provided sufficient loading resistance with maximum possible load at 500 kg and safeguards, with

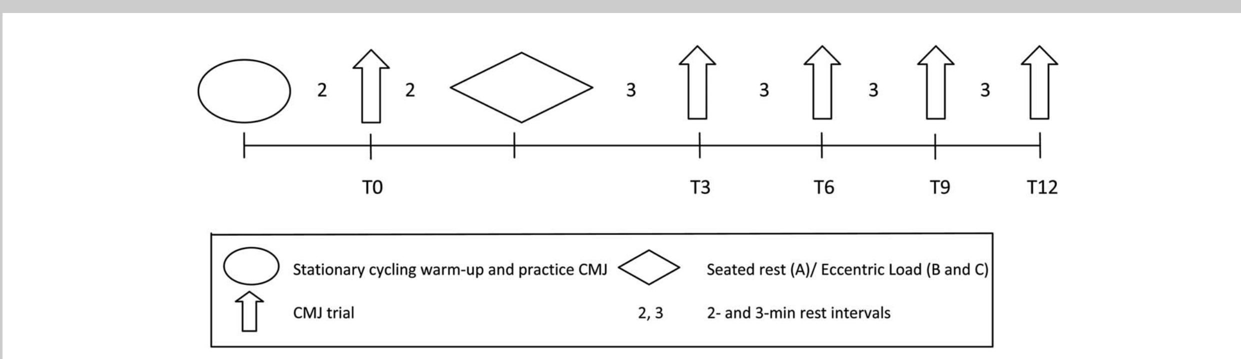

Figure 2. Schematic representation of testing protocol and timeline.

user-controlled release catch at the start and a self-spotting mechanism at the end of exercise.

Kinetic and kinematic data of the CMJ trials were collected using a combined force plate and linear positional transducer system. The maximum vertical displacement (D_{max}) achieved for each jump trial is determined using the linear position transducer (Fitness Technology, Adelaide, Australia) mounted above the participant, using an overhead boom, with a cable attached to the participant via an adjustable snug-fitting vest. The transducer was calibrated using a known vertical distance of 1 m. Measurements for peak power (P_{peak}) were taken off a force plate (Fitness Technology, Adelaide, Australia) mounted onto a power cage (Fitness Technology) on which the vertical jump trials were carried out. The equipment used was similar to the set up in the study done by Sheppard and Young (35). The force plate was calibrated before each testing session, using a spectrum of known loads and used to measure the ground reaction force from the participant's vertical jumps. Both the force plate and linear position transducer were interfaced with computer software (Fitness Technology) that allowed direct measurements of displacement-time and power-time characteristics of the CMJ trials.

Statistical Analyses

For each condition and time point, the best CMJ trial of the 3 attempts was selected for analysis based on the P_{peak} generated. The corresponding D_{max} was then read off the same selected CMJ trial at each time point.

Results are expressed as mean ± *SD* unless otherwise stated. Differences in vertical jump performance parameters between 0RM and eccentric preloading conditions (105RM and 125RM) were analyzed for statistical significance with a spreadsheet via unequal variance *t* statistic (19,20). The difference within condition between control time point and posteccentric load time course T3, T6, T9, and T12 was analyzed via the same statistical method. The difference was analyzed via log-transformed values, to reduce bias arising from nonuniformity of error. Precision of the estimates of observed effects was indicated with confidence limits (difference, ±90% CL). Differences between conditions were assessed using Cohen's effect size (Cohen's d) with modified descriptors (Hopkins) (18). Effect sizes, presented with confidence limits (ES; ±90%CL), were assessed using these criteria: <0.2, trivial; 0.2–0.6, small; >0.6–1.2, moderate; >1.2–2.0, large; and >2.0, very large. Pairwise comparisons were carried out on differences between conditions at each time point and within condition between control and posteccentric loading time points. Statistical significance was accepted at $p \leq 0.05$.

Results

Descriptive data and results of statistical analysis for differences of the measured parameters (P_{peak} and D_{max}) between conditions are presented in Tables 1 and 2.

There were no significant differences ($p > 0.05$) in both measured parameters (P_{peak} and D_{max}) between 0RM and eccentric load conditions (105RM and 125RM) at control time point. This shows that vertical jump performance is kept constant at baseline or control time point during each of the testing sessions. There was also no significant difference in both P_{peak} and D_{max} between 105RM and 125RM throughout the time course.

At T3 and T6, P_{peak} was significantly higher in both 105RM and 125RM when compared with 0RM (Table 1). In control condition (0RM), there was a significant decrement in P_{peak} comparing control with all posteccentric load time points T3, T6, T9, and T12 (ES = −0.19; ±0.09, −0.25; ±0.06, −0.23; ±0.08, −0.25; ±0.08), whereas no difference in power was noted over similar comparisons in 105RM and 125RM. At T3, D_{max} was significantly higher for both 105RM and 125RM when compared with 0RM, whereas at T6, significant improvement was seen in 105RM (Table 2). Within 105RM, compared with control time point, D_{max} was significantly improved at T3 (ES = 0.19; ±0.15) and T6 (ES = 0.2; ±0.12).

Table 1. Peak power (P_{peak}) throughout the time course; pre-eccentric and posteccentric load (T3, T6, T9, and T12) with eccentric load at 105% (105RM) and 125% (125RM) 1RM compared with control condition (0RM).

			Comparison to control condition (0RM)		
Time	Condition	Power (W), mean ± *SD*	Difference; ±90% CL	ES; ±90% CL	*p*
Pre	0RM	4280 ± 767			
	105RM	4229 ± 789	−51.4; ±68.6	−0.08; ±0.1	0.21
	125RM	4271 ± 816	−8.8; ±77.1	−0.02; ±0.1	0.695
T3	0RM	4143 ± 754			
	105RM	4305 ± 876	161.1; ±114.2	0.2; ±0.15	0.037*
	125RM	4314 ± 848	172.3; ±105.7	0.22; ±0.13	0.01*
T6	0RM	4102 ± 781			
	105RM	4237 ± 842	134.4; ±66.1	0.17; ±0.09	0.006*
	125RM	4264 ± 768	162; ±69.5	0.22; ±0.09	0.001*
T9	0RM	4113 ± 757			
	105RM	4199 ± 809	85.1; ±81.3	0.11; ±0.11	0.094
	125RM	4216 ± 818	102.8; ±91.7	0.13; ±0.13	0.093
T12	0RM	4102 ± 761			
	105RM	4200 ± 799	98.2; ±83.1	0.13; ±0.12	0.084
	125RM	4152 ± 809	50.2; ±91.5	0.06; ±0.13	0.416

*Indicates a significant difference from 0RM ($p \leq 0.05$).

TABLE 2. Maximum vertical displacement (D_{max}) throughout the time course; pre-eccentric and posteccentric load (T3, T6, T9, and T12) with eccentric load at 105% (105RM) and 125% (125RM) 1RM compared with control condition (0RM).

			Comparison to control condition (0RM)		
Time	Condition	Displacement (cm), mean ± *SD*	Difference; ±90% CL	ES; ±90% CL	*p*
Pre	0RM	44.1 ± 7.2			
	105RM	43.2 ± 7.2	−0.01; ±0.01	−0.12; ±0.15	0.172
	125RM	43.5 ± 7.7	−0.01; ±0.01	−0.09; ±0.13	0.223
T3	0RM	42.2 ± 7.8			
	105RM	44.5 ± 7.3	−0.02; ±0.02	0.3; ±0.23	0.038*
	125RM	44.3 ± 8.3	−0.02; ±0.01	0.25; ±0.17	0.017*
T6	0RM	43.2 ± 7.3			
	105RM	44.7 ± 7.7	0.01; ±0.01	0.2; ±0.16	0.047*
	125RM	44.4 ± 8.0	0.01; ±0.01	0.15; ±0.17	0.137
T9	0RM	43.1 ± 7.3			
	105RM	44.1 ± 7.8	0.01; ±0.01	0.12; ±0.18	0.243
	125RM	43.9 ± 7.7	0.01; ±0.01	0.1; ±0.19	0.368
T12	0RM	42.8 ± 6.4			
	105RM	43.4 ± 7.4	0.01; ±0.01	0.07; ±0.16	0.444
	125RM	42.9 ± 8.0	0; ±0.02	−0.01; ±0.23	0.928

*Indicates a significant difference from 0RM ($p \leq 0.05$).

In the present study, there was no effect of the order of trial administration on the P_{peak} and D_{max} for the 3 different conditions ($p > 0.05$) at T3 and the coefficients of variation (CV) for P_{peak} and D_{max} between the familiarization and control trial (0RM) were 2.9 and 6.4%, respectively. The corresponding intra-class correlation coefficients (ICCs) were 0.98 and 0.90 for P_{peak} and D_{max}, respectively.

DISCUSSION

The objective of the present study was to examine the effects of different intensities of eccentric preconditioning load on subsequent performance throughout the time course after loading. The results of the present study suggest that eccentric preconditioning is effective as PAP in improving vertical jump performance at both 105 and 125% of 1RM. This effect is observed to be most pronounced between 3 to 6 minutes after eccentric loading. Given that the smallest worthwhile enhancement for P_{peak} and D_{max} were 0.9 and 1.9%, respectively, calculated as 0.3 of the coefficient of variation in performance (18), the improvements in P_{peak} and D_{max} reported here are thus sufficient to be meaningful to the recreationally active participants tested. It remains to be determined whether similar degree of ergogenic effect can be observed in well-trained or highly trained individuals. The observed results are likely to be related to the 2 phenomena that have been extensively discussed in existing literature–AEL leading to immediate improved concentric performance within a SSC and PAP of muscle units.

Four possible mechanisms have been theorized as possible contributors to the improved contractile mechanisms after AEL (3,8,38). The first 3 mechanisms were reported in the study by Walshe et al. (38). The first possible explanation is the increased neural stimulation from greater stretch of intrafusal muscle fibers from greater eccentric load, resulting in a reflex arc in which there is increased stimulation of γ motor neurons signaling the brain to increase firing rate of α motor neurons leading to increased contractile force. The second proposed mechanism is that of increased stretch of parallel and series musculotendinous structures leading to increased elastic recoil, which is mechanistically similar to a stretched elastic band with increased recoil forces. A third mechanism is that increased force production from reduced myofibrillar displacement due to stored elastic energy in fibers at start of concentric phase of contraction. The final proposed mechanism is that of increased preloading, which has been discussed as perhaps the mechanism which is the greatest contributor to the enhanced subsequent concentric performance from prior eccentric loading (3,8). The AEL allows the agonistic muscles to achieve an active preparatory state with a portion of the actin–myosin cross-bridges being attached before concentric action, thereby increasing force and power production early in the concentric phase. This mechanism is likely related to PAP and important in explaining the findings in the present study.

Muscular performance is affected by the muscle's contractile history. Increased muscular activity results in fatigue with decreased neuromuscular force generation (30). However, previous muscular activity can also improve subsequent force generation and enhance strength and power performance (2,31). This latter phenomenon is termed PAP. The physiological mechanisms behind PAP remain unclear, with 2 main postulations being reported in current literature (37). The first is that of increased phosphorylation of myosin regulatory light chains, increasing the sensitivity of actin–myosin cross-bridges to calcium ions released from the sarcoplasmic reticulum, hence increasing the rate constant for cross-bridge attachment. The second mechanism is the increased excitation potential from previous contractions leading to recruitment of higher threshold fast twitch motor units responsible for explosive activities.

The type of conditioning contraction is a parameter that could affect PAP. Where a SSC muscular activity like CMJ performance is of interest, as in the present study, eccentric preconditioning could affect subsequent force generation, peak power attained, and thus, vertical jump performance. Mixed results have been observed from studies investigating dynamic back squats on CMJ performance, with Jones and Lees (24) and Kilduff et al. (25) reporting no difference and significant improvement, respectively, in subsequent measurements. In previous studies, mainly isometric and dynamic (eccentric–concentric) contractions have been used to examine PAP, with subsequent measures being made on activities involving performance of ballistic movements such as CMJ or bench throws. The use of eccentric contraction in the present study may be more specific to the contractile demands of the measured activity involving SSC.

In examining the optimal eccentric load, it is observed in the present study that there is significant improvement in P_{peak} at 3 and 6 minutes when either 105 or 125% 1RM eccentric load is used, when compared with control condition at corresponding time points. With the 105% 1RM loading condition, significant improvement is also observed in maximum vertical displacement at 3 and 6 minutes while this improvement is seen with 125% load only at 3 minutes. It is physiologically impossible to apply loads in excess of one's current 1RM for any given movement concentrically or over the entire eccentric–concentric cycle for purposes of PAP or preconditioning. The above, along with the aforementioned fact that the eccentric contractions are capable of higher levels of torque and force compared with concentric contractions, would logically suggest that an eccentric resistance greater than an individual's 1RM for a given exercise is required for purposes of PAP. Thus, in the present study, it is not only within physiological limits but also in the authors' opinion, necessary to impose loads in excess of 1RM for purposes of eccentric PAP.

In recent times, studies involving eccentric preconditioning have been conducted in comparison with other different modes of contractions as preconditioning, on both upper and lower body muscular performance. Esformes et al. (12) compared different conditioning contractions including eccentric contractions on upper-body ballistic bench throw performance and found no difference between eccentric and other modes (isometric, concentric, and dynamic) of preconditioning stimulus at 12 minutes. Bogdanis et al. (4) found significant improvement in CMJ performance with eccentric preloading at 70% 1RM half-squats compared with control between 6 and 10 minutes after exercise, but no difference when postload measurements were compared with baseline performance. The preconditioning stimulus used in these studies was a uniform submaximal load of 3RM with a single time point (12 minutes) sampled in study by Esformes et al. (12) and with the subject performing movements short of full range of motion in study by Bogdanis et al. (4). These are in contrast to the present study, which involves the use of loads exceeding 1RM for eccentric activation with the participants performing full range of motion made possible by use of the inherent safety of the hip sled machine and changes in performance being sampled across a time course postactivation. Significant findings from the present study may be attributed to these inherent protocol characteristics.

Any muscle contraction, conditioning or otherwise, causes fatigue, and the interaction between PAP and fatigue has a direct effect on the subsequent measured explosive muscular performance. Thus, obtaining a PAP-induced window of performance after any preconditioning protocol is a matter of the evolving balance between potentiation or warm-up and fatigue, with the former hopefully declining more slowly than the latter. The protocol and test intervals had been planned to balance data resolution and adequate wash-out between subsequent data collection points. Results from the present study show significant improvement in vertical jump displacement at 3 and 6 minutes compared with control time point with 105% eccentric load, which is in close agreement to that of study by Lowery (28), in which effects from volume-controlled preconditioning peaked at 4 minutes and waned by 8 minutes. This period is likely to represent the time window for optimal performance posteccentric PAP, when the positive effect of PAP in warm-up offsets muscular fatigue, resulting in an overall improved performance. There was significantly decreased power throughout the time course compared with control and displacement at T3 in the control condition. A possible explanation for this observation is the loss of warm-up effect of the generic cycling and CMJ practice included in the study protocol. The practice CMJ may have served as potentiating stimulus for the control CMJ trial, whereas subsequent trials are may be unpotentiated after the 10-minute rest period. The CV and ICC for P_{peak} and D_{max} between the familiarization and control trial (0RM) were 2.9 and 6.4% and 0.98 and 0.90, respectively, which compared favorably with a previous study by Hori et al. (21). The reliability of our performance data is likely to have been improved by the use of a simple jumping motor skill and the addition of the familiarization session. Furthermore, there was no order or learning effect on any of the performance variables ($p > 0.05$), therefore suggesting that the participants did not require further familiarization, and the performance test was appropriate to reliably assess jumping performance.

The 2 main limitations in the study are the training status of the participants and method of serial testing used that may influence learning or fatiguing effects. The training status and characteristics of the study population may have an impact on the results and extension of findings to athletes. It was previously shown that recreational athletes did not respond to potentiation in jump performance and trained athletes to a PAP protocol (13). Other studies also reported reduced force and power jump parameters displayed by recreational athletes, compared with well-trained athletes (6,39). In terms of participant characteristics, it was shown that strength (15), strength-to-power ratio (33), and muscle fiber composition (17) contribute to differences in response to potentiating stimuli. Thus, eccentric PAP studies on elite professional athletes with background of systematic training or within homogenous groups for aforementioned characteristics may yield even greater improvements. The method of serial testing used in the current and other studies is also a limitation as subsequent trials may be affected by the previous CMJ, which may serve as potentiating or fatiguing stimuli. Future studies may thus examine the effect of eccentric preconditioning on performance throughout the time course in isolated trials.

Research can also be carried out to define the mechanism underlying eccentric preconditioning, some techniques that can possibly be used includes musculoskeletal ultrasonography, electromyography, and muscle biopsy. As it has been shown that eccentric training leads to greater neural adaptation and hypertrophy compared with concentric contractions (22), eccentric PAP as a training tool can be explored in studies looking into chronic adaptations and contribution toward strength and power performance. Future research may also investigate variations of factors known to affect the balance of potentiation and fatigue, such as exercise volume, intensity, and recovery times to improve the understanding and application of eccentric exercise as a mode of PAP. The main goal of these proposed studies is to assist both sport and strength and conditioning coaches with methods to train SSC eccentric stretch triggers, to stimulate concentric responses more efficiently.

Practical Applications

Results from the present study clearly demonstrate a small but significant improvement in vertical jump performance in an intermediate time window after high-intensity eccentric preconditioning. Coaches involved in jumping sports can explore the possibility of using eccentric preconditioning stimuli as part of their warm-up protocol. The relative load selected for such a protocol should be just above the athlete's predetermined 1RM for the selected exercise, and this intervention can be applied in the 3- to 6-minute window before the intended activity. The prospects of improved jump height should be particularly exciting for jumping athletes and across disciplines requiring the production of explosive ballistic force, whereas the increased peak power achieved should appeal to strength and conditioning coaches and applied sports scientists. This can be applied as a preassessment and precompetition strategy to enhance performance in sport-specific assessments such as NFL Combine assessments and events such as track and field (sprints, jumps, and throws), swimming (sprints and diving), and winter sports (bob sled and speed skating), where power and acceleration are key physical attributes.

Past research has produced largely inconclusive results where explosive activities are concerned. This inconsistency appears to be largely because of the interaction between fatigue and potentiation effects inherent in a warm-up protocol. Thus, in the selection of an appropriate protocol, especially in the precompetition setting, it is important for the coach or trainer to understand the fine line between potentiation and fatigue. An inappropriate PAP protocol may negatively impact performance, especially in short-duration events. Besides the specified parameters of a PAP protocol, one should also consider other factors such as the specific exercise or sport, muscle groups involved, type of muscle action, number of repetitions or sets, and rest periods. Individual- or team-specific differences such as age, gender, training status, and experience should also be determined and accounted for. In short, there is no "one-size-fits-all" approach to optimal performance. Interventions such as eccentric PAP should be trialed on multiple training sessions, individualized, and fine-tuned for the athlete or team before consideration for use in competitions.

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References

1. Baechle, TR and Earle, RW. *Essentials of Strength Training and Conditioning* (3rd ed.). Champaign, IL: Human Kinetics, 2008.
2. Baker, D. Acute effects of alternating heavy and light resistances on power output during upper-body complex power training. *J Strength Cond Res* 17: 493–497, 2003.
3. Bobbert, MF, Gerritsen, KGM, Litjens, MCA, and Van Soest, AJ. Why is countermovement jump height greater than squat jump height?. *Med Sci Sports Exerc* 28: 1402–1412, 1996.
4. Bogdanis, GC, Tsoukos, A, and Veligekas, P. Effects of different muscle types with equal Impulse of conditioning activity on post-activation potentiation. *J Strength Cond Res* 28: 2521–2528, 2014.
5. Brandenburg, J and Docherty, D. The effects of accentuated eccentric loading on strength, muscle hypertrophy, and neural adaptations in trained individuals. *J Strength Cond Res* 16: 25–35, 2002.
6. Chiu, LZF, Fry, AC, Weiss, LW, Schilling, BK, Brown, LE, and Smith, SL. Post activation potentiation response in athletic and recreationally trained individuals. *J Strength Cond Res* 17: 671–677, 2003.
7. Connolly, DA, Sayers, SP, and McHugh, MP. Treatment and prevention of delayed onset muscle soreness. *J Strength Cond Res* 17: 197–208, 2003.
8. Cronin, JB, Mcnair, PJ, and Marshall, RN. Magnitude and decay of stretch-induced enhancement of power output. *Eur J Appl Physiol* 84: 575–581, 2001.
9. Doan, BK, Newton, RU, Marsit, JL, Triplett-McBride, TN, Koziris, PL, Fry, AC, and Kraemer, WJ. Effects of increased eccentric loading on bench press 1RM. *J Strength Cond Res* 16: 9–13, 2002.
10. Doss, WS and Karpovich, PV. A comparison of concentric, eccentric, and isometric strength of elbow flexors. *J App Physiol* 20: 351–353, 1965.

11. Ebben, WP and Watts, PB. A review of combined weight training and plyometric training modes: Complex training. *J Strength Cond Res* 20: 18–27, 1998.
12. Esformes, JI, Keenan, M, Moody, J, and Bampouras, TM. Effect of different types of conditioning contraction on upper body post-activation potentiation. *J Strength Cond Res* 25: 143–148, 2011.
13. Fountas, M, Bakaloudi, E, Bassa, E, Xenofontos, A, and Kotzamanidis, C. The effect of high-intensity half-squat to the jump performance in recreationally active men. *J Phys Ed Sport* 12: 310–315, 2012.
14. Godard, MP, Wyngand, JW, Caripinelli, RN, Catalano, S, and Otto, RN. Effects of accentuated eccentric resistance training on concentric knee extensor strength. *J Strength Cond Res* 12: 1519–1533, 1998.
15. Gourgoulis, V, Aggeloussis, N, and Kasimatis, P. Effect of a submaximal half-squats warm-up program on vertical jumping ability. *J Strength Cond Res* 17: 342–344, 2003.
16. Gouvea, AL, Fernandes, IA, Cesar, EP, Silva, WA, and Gomes, PS. The effect of rest intervals on jumping performance. *J Sports Sci* 31: 459–467, 2012.
17. Hamada, T, Sale, DG, and MacDougall, JD. Interaction of fibre type, potentiation and fatigue in human knee extensor muscles. *Acta Physiol Scand* 178: 165–173, 2003.
18. Hopkins, WG. A scale of magnitudes for effect statistics. Available at: sportsci.org/resource/stats/effectmag, 2002. Accessed December 4, 2014.
19. Hopkins, WG. How to analyse a straightforward crossover trial (Excel spreadsheet). Available at: sportsci.org/resource/stats/xcrossover.xls, 2003. Accessed December 4, 2014.
20. Hopkins, WG. A spreadsheet for analysis of straightforward controlled trials. Available at: sportsci.org/jour/03/wgtrials.htm, 2003. Accessed December 4, 2014.
21. Hori, N, Newton, RU, Kawamori, N, McGuigan, MR, Kraemer, WJ, and Nosaka, K. Reliability of performance measurements derived from ground reaction force data during countermovement jump and the influence of sampling frequency. *J Strength Cond Res* 23: 874–882, 2009.
22. Hortobagyi, T and Katch, FI. Eccentric and concentric torque-velocity relationships during arm flexion and extension- Influence of strength level. *Eur J Appl Occup Physiol* 60: 395–401, 1993.
23. Jo, E, Judelson, DA, Brown, LE, Coburn, JW, and Dabbs, NC. Influence of recovery duration after a potentiating stimulus on muscular power in recreationally trained individuals. *J Strength Cond Res* 24: 343–347, 2010.
24. Jones, P and Lees, A. A biomechanical analysis of the acute effects of complex training using lower limb exercises. *J Strength Cond Res* 17: 694–700, 2003.
25. Kilduff, LP, Bevan, HR, Kingsley, MIC, Owen, NJ, Bennett, MA, Bunce, PJ, Hore, AM, Maw, JR, and Cunningham, DJ. Postactivation potentiation in professional rugby players: Optimal recovery. *J Strength Cond Res* 21: 1134–1138, 2007.
26. Kilduff, LP, Owen, NJ, Beven, HR, Benett, MA, Kingsley, MIC, and Cunningham, DJ. Influence of recovery time on post-activation potentiation in professional rugby player. *J Sports Sci* 26: 795–802, 2008.
27. Komi, VP and Bosco, C. Utilisation of stored elastic energy in leg extensor muscles by men and women. *Med Sci Sports Exerc* 10: 261–265, 1978.
28. Lowery, RP, Duncan, NM, Loenneke, JP, Sikorski, EM, Naimo, MA, Brown, LE, Wilson, FG, and Wilson, JM. The effects of potentiating stimuli intensity under varying rest periods on vertical jump performance and power. *J Strength Cond Res* 26: 3320–3325, 2012.
29. Raihimi, R. The acute effects of heavy versus light-load squats on sprint performance. *J Phys Ed Sports* 5: 163–169, 2007.
30. Rassier, DE and Macintosh, BR. Coexistence of potentiation and fatigue in skeletal muscle. *Braz J Med Biol Res* 33: 499–508, 2000.
31. Rixon, KP, Lamont, HS, and Bemben, MG. Influence of type of muscle contraction, gender, and lifting experience on post-activation potentiation performance. *J Strength Cond Res* 21: 500–505, 2007.
32. Rodgers, KL and Berger, RA. Motor-unit involvement and tension during maximum, voluntary concentric, eccentric, and isometric contractions of the elbow flexors. *Med Sci Sports Exerc* 6: 253–259, 1974.
33. Schneiker, K, Billaut, F, and Bishop, D. The effects of preloading using heavy resistance exercise on acute power output during lower-body complex training (abstract). Book of Abstracts of the 11th Annual Congress, European College of Sports Science, 2006.
34. Sheppard, JM, Newton, R, and McGuigan, M. The effect of accentuated eccentric load on jump kinetics in high performance volleyball players. *Int J Sports Sci Coaching* 2: 267–273, 2007.
35. Sheppard, JM and Young, K. Using additional eccentric load to increase concentric performance in the bench throw. *J Strength Cond Res* 24: 2853–2856, 2010.
36. Shroeder, ET, Hawkins, SA, and Jacque, SV. Musculoskeletal adaptations to 16 weeks of eccentric progressive resistance training in young women. *J Strength Cond Res* 18: 227–235, 2004.
37. Tillin, NA and Bishop, D. Factors modulating post-activation potentiation and its effect on performance of subsequent explosive activities. *Sports Med* 39: 147–166, 2009.
38. Walshe, AD, Wilson, GJ, and Ettema, GJC. Stretch-shorten cycle compared with isometic preload: Contributions to enhanced muscular performance. *J Appl Physiol* 84: 97–106, 1998.
39. Wilson, JM, Duncan, NM, Marin, PJ, Brown, LE, Loenneke, JP, Wilson, SMC, Jo, E, Lowery, RP, and Ugrinowitsch, C. Metaanalysis of postactivation potentiation and power: Effects of conditioning activity, volume, gender, rest periods, and training status. *J Strength Cond Res* 27: 854–859, 2013.