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TITLE PAGE

Title:

Post-activation potentiation following different modes of exercise, R-31239, Revision 1

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Post-activation potentiation following exercise

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ABSTRACT

The performance characteristics of skeletal muscle are transient in nature and have been shown to be significantly affected by its contractile history, where the phenomenon of acute enhancement is termed post-activation potentiation (PAP). Acute enhancement of dynamic activity has been observed when preceded by resistance exercises, however little information exists for plyometric activity as a conditioning stimulus. In addition, no study has examined PAP effects on more than one subsequent performance trial. The purpose of the present study was to determine whether countermovement jump (CMJ) performance could be enhanced if preceded by heavy resistance exercise or by dynamic plyometric activity over three trials. Thirteen anaerobically trained male subjects (mean \pm SD: age, 22 \pm 3 years; height, 182.4 \pm 4.3 cm; body mass, 82.7 \pm 9.2 kg) performed in a counterbalanced order 3 half squats using a 3 repetition maximum loading (SQUAT), a set of 24 contacts of lower body plyometric exercises (PLYO), or a control of no activity (REST) 5 min prior to each CMJ. Three sets of each treatment and CMJ were performed in total and maximal displacement (d_{\max}), peak power (P_{peak}) and peak vertical force (F_{peak}) were recorded, while rate of force development (RFD) and relative force ($F / \text{body mass}$) were calculated for every trial. No significant differences were revealed for any of the other variables, but greater displacement was found for SQUAT compared to REST or PLYO, while no differences were revealed for any of the conditions for the repeated trials. Although heavy resistance-induced PAP seems to enhance jump height compared to REST or PLYO in repeated CMJ performance, it has no additional benefit on repeated trials.

KEYWORDS: plyometrics, complex training, reactive index, power performance

INTRODUCTION

Performance of skeletal muscle is significantly affected by its contractile history, as acute responses are affected by the muscle contractions preceding the activity (22). Increased muscular activity results in decreased neuromuscular force generation and fatigue (20), having a negative impact on subsequent strength and power performance. In contrast, optimal previous muscular activity can increase force generation and improve subsequent strength and power performance, a phenomenon termed post-activation potentiation (PAP, 22).

This enhancement has been primarily attributed to two mechanisms; regulatory light chains phosphorylation and increased recruitment of motor units. Regulatory light chains phosphorylation has been shown to increase the sensitivity of the actin-myosin interaction to the Ca^{2+} released from the sarcoplasmic reticulum and alter the structure of the myosin head, resulting in a higher force-producing state for the myosin cross-bridges (20). For the second mechanism, it is postulated that previous contractions increase the excitation potential across the spinal cord, which lasts for several minutes following the initial contractions, resulting in increased post-synaptic potentials and, subsequently, increased force generation capacity (8).

One of the factors affecting PAP is the intensity of the conditioning activity, with higher intensity activities appearing to be more effective (6, 22, 27). Indeed, the majority of studies examining the effect of PAP on athletic performance have reported positive effects when using heavy weights prior to explosive movements such as short sprints, vertical jumps or explosive strength jumps (2, 16, 29). Chiu et al (2) used 5 sets of 1 back squat repetition at 90% of the subject's one repetition maximum (1RM) and reported a significant improvement in jump squat power using 30%, 50% and 70% of 1RM. Their results agree with findings by

Weber et al (29), who reported an increase in vertical ground reaction force and jump height following 5 repetitions at 85% of 1RM. McBride et al (16) used 3 repetitions at 90% of 1RM and reported a significant improvement in 40-m sprinting times of football players. Finally, Kilduff et al (13) using a 3RM back squat set reported a 6.8% increase in countermovement jump (CMJ) performance. Conversely, Jones and Lees (12) reported no improvement in CMJ following 5 squat repetitions at 85% of 1RM. Nevertheless, there was no reduction in performance, suggesting that execution of heavy resistance exercise prior to CMJ was not detrimental. It is possible, therefore, that Jones and Lees did not observe fatigue due to an induced PAP, as fatigue and PAP are initiated together following muscular contractions (20).

There is little evidence in the literature to indicate that PAP can affect maximum force generation (26). However, PAP can improve rate of force development (RFD; 6, 22, 26), which is an important factor in explosive sport activities where high power outputs are required. Such high power output in explosive sports is usually achieved by substantial utilisation of the stretch-shortening cycle (plyometrics). Despite the potential of plyometric exercises as a PAP stimulus, little is known about the acute effect plyometric exercises have on subsequent muscular performance. Masamoto et al (15) examined the effect of three double-leg tuck jumps and 2 depth jumps on subsequent 1RM squat performance and reported a 3.5% improvement in the load lifted. McBride et al (16) used a loaded CMJ for a single set of 3 repetitions at 30% of 1RM before a 40-m sprint but found no differences. The lack of any difference in performance was attributed to the single set being insufficient to induce PAP. The small number of studies and the contradicting results merit further investigation of the ability of plyometric exercises to induce PAP.

The potential impact of PAP on explosive sports raises another issue that merits further investigation. Many explosive sports, such as jumps and throws in athletics and Olympic weightlifting, involve repeated trials. Therefore, it is important to gain an understanding of PAP effects on repeated performances, e.g. repeated CMJ trials. Smilios et al (25) assessed the jump height of a countermovement jump at six time points. These time points were at baseline, following each set of conditioning jumps (3 sets) and at 5 and 10 minutes recovery. The findings indicated that following an initial improvement in CMJ performance, the jump height subsequently remained similar or decreased following the first loaded jump squat. However, as heavy weights have been shown to elicit PAP more effectively (6, 22, 27), a higher load may have yielded different results. Lastly, no information exists on the ability of plyometric exercises to elicit PAP on repeated performances.

Therefore, the aim of the present study was to a) examine PAP effects induced by heavy weight or plyometric exercises on repeated trials, and b) compare performances in repeated trials between the two modes of exercise. It was hypothesized that a) both heavy weights and plyometric exercises would induce PAP, and b) plyometric exercises would have a greater impact on subsequent performance than heavy weight exercise.

METHODS

Experimental approach to the problem

The PAP effects induced by heavy weight and plyometric exercises on repeated trials and any potential differences between the two conditioning stimuli were examined using a randomized, counterbalanced, repeated measures design. Subjects performed three countermovement jumps (CMJ) on 3 separate occasions. On each occasion each CMJ was

preceded by a conditioning stimulus, with the sequence repeated three times (Figure 1). The conditioning stimuli were 1) resistance exercise (SQUAT), 2) plyometric exercise (PLYO), or 3) inactivity (REST). The plyometric exercise conditioning stimulus consisted of four different plyometric exercises totalling 24 foot contacts, while one set of 3 repetitions at 3RM was used as the resistance exercise conditioning stimulus. REST served as a control condition and was used to compare the effects of contractile history between subjects using inactive recovery and those using a preconditioning stimulus. Maximal displacement (d_{\max}), peak power (P_{peak}) and peak vertical force (F_{peak}) were recorded from a force plate, while rate of force development (RFD) and relative force ($F / \text{body mass}$) were calculated for every trial. The variables examined were selected as they are commonly used for assessing explosive performance and can provide an indication of any PAP effects.

Subjects

Thirteen male, competitive athletes (mean \pm SD: age, 22 ± 3 years; height, 182.4 ± 4.3 cm; body mass, 82.7 ± 9.2 kg) volunteered to participate in the current investigation and provided written, informed consent. The subjects participated in sports or events where explosive power was a significant aspect (100/200/400 m, $n = 7$; 400m hurdles, $n = 1$; pole vault, $n = 1$; long jump, $n = 2$; rugby, $n = 2$). When testing took place, all subjects were in the competitive phase of their training cycle, although at different points, as the athletics season finishes in the summer while the rugby season starts in spring. All subjects included regular and planned resistance training as part of their sport training programme for at least 2 years prior to the study. Their training included a minimum of three sessions per week, with training loads ranging from 30% - 90% of 1RM, depending on the phase of their training cycle. Finally, the subjects were free of any medical conditions or lower limb injuries in the 6 months prior to

the investigation. The study was approved by the University of Wales Institute, Cardiff Ethics Committee.

Procedures

All subjects initially visited the laboratory to ensure familiarity with the half squat (90° knee flexion), the plyometric exercises, and the CMJ technique and to have their age, height and weight recorded. Height was measured to the nearest 0.1 cm using a stadiometer (Harpden, UK) and weight was measured using a calibrated balance beam scale (Seca, UK) and recorded to the nearest 0.1 kg.

Subjects were then required to complete a set of stabilisation tests to determine whether they had sufficient stabilisation strength to perform the plyometric exercises. These tests comprised of a static stand (hip flexed), single leg squat, hop for distance, hop down (from a 0.3 m platform), a repetitive jump test and to be able to squat 1.5 times their body mass (23). Form and technique were observed and used to identify successful completion of the tests, with all subjects successfully completing all the stabilisation strength tests. Each subject's 3RM half squat was then determined, with 3RM defined as a load that caused failure on the third repetition without loss of proper exercise technique. To establish the 3RM load, subjects attempted 3 repetitions of a load and, if successful, increased the loading. A 5 min rest interval was allowed between trials, with 3 to 5 trials typically required for determining each subject's 3RM.

The subjects then visited the laboratory on three separate sessions. A standardised dynamic warm up protocol was used for all sessions, which consisted of 400 m jogging and 4 repetitions of dynamic drills over 15 m (heel flicks, high knee jogging, walking lunges and

walking hamstring sweeps). Following the standardised warm up, the subjects were randomly assigned to one of the experimental groups; inactivity (REST), plyometric exercise (PLYO) or heavy weight exercise (SQUAT). REST executed no additional warm up. PLYO performed one set of 6 contacts of alternate speed bounds, right leg speed hops, left leg speed hops and vertical bounds (total foot contacts = 24), with a 15 sec resting interval allowed between each exercise. SQUAT subjects performed 2 sets of 6-10 half squats (90° knee flexion) at 60% and 85% of 3RM respectively with a minimum of 2 min rest between sets. Following the condition-specific warm up, a minimum rest of 2 min was allowed.

The subjects then performed the conditioning stimulus (described below) with 5 min rest and, subsequently, three CMJs with 10 min rest. This sequence was performed 3 times to approximate a sporting situation, as a number of events in Athletics have repeated attempts. A schematic diagram of the experimental procedure can be seen in Figure 1.

FIGURE 1 ABOUT HERE

The conditioning stimulus for the PLYO group was 1 set of 6 foot contacts per plyometric exercise (alternate speed bounds, right leg speed hops, left leg speed hops and vertical bounds), totalling 24 foot contacts per subject per trial. A 15 s resting interval between each exercise was allowed. Subjects were specifically instructed to minimise ground contact time and maintain technique on each repetition. The total time required for each subject to complete the plyometric exercises was approximately 70 s.

The conditioning stimulus for the SQUAT group was one set of three half squats at 3RM, performed as quickly as possible using a standard 20 kg Olympic barbell and weight plates

(Ivanko, Sweden). All resistance exercises were performed within the confines of a weightlifting safety cage. Subjects were permitted to use weightlifting belts, if desired. The use of support knee wraps and weightlifting body suits were not permitted. According to the International Powerlifting Federation rules, a lift was deemed to be successful if the subject could descend until the inguinal fold was lower than the patella and rise without help. Approximately 15 s were required by each subject to complete the squat exercise.

Following the conditioning stimulus, subjects remained inactive for a period of 5 min, before performing 3 CMJs, separated by approximately 8 seconds each. The CMJ is commonly used for assessing lower limb explosive power and has been shown to be highly reliable (Intraclass Correlation Coefficient = 0.97; 14). In studies using similar CMJ protocols to ours, intraclass correlation coefficients were also high ($r = 0.95$; 25). CMJs were initiated from an upright standing position and upon command the subjects squatted (the degree of knee bend used by each subject was self-determined) and then immediately after jumped vertically. The subjects were specifically instructed to aim for maximum height. To isolate the contribution from the lower limbs, subjects were requested to place their hands on their hips throughout each jump. A 10 min rest interval was provided between the CMJs and the following conditioning stimulus. This rest interval was used to replicate the approximate temporal demands during the events of Athletics competitions. Following the third and final set repetition, subjects were asked to undertake a cool down consisting of light jogging and stretching.

Maximal displacement (d_{\max}), peak power (P_{peak}) and peak vertical force (F_{peak}) were measured on a Kistler force platform with an internal charge amplifier (Model 9287ba, Kistler, Winterthur, Switzerland). The force data were sampled at 1000 Hz for 3 s and analysed using Bioware software (version 3.2.6, Kistler, Winterthur, Switzerland). Rate of

force development (RFD) was calculated as maximum force / time to maximum force (30). Finally, relative force (RelF) was calculated as absolute force / body mass. For all measurements, the highest CMJ was used from each trial for each condition to reduce variability (18).

Subjects refrained from any strenuous activities or resistance/ plyometric training at least 24 hours before testing. All tests took place at the same time of the day and with a minimum of 24 hours intervening.

Statistical analyses

Data were checked for normality using the Shapiro-Wilks test. As data were found to deviate from normal distribution, Friedman's test was used to examine for differences within trials for all performance measures (d_{\max} , P_{peak} , F_{peak} , RFD and RelF). Where a difference was revealed, Wilcoxon's test was used to identify those differences. Significance level was set at $P \leq 0.05$. As the measurements were directly or indirectly intercorrelated, no adjustments were made for multiple comparisons, but exercised caution in the interpretation of the results (19, 21). All statistical analyses were conducted using SPSS v14.0.

RESULTS

A significant difference was revealed for displacement ($P = 0.009$; Figure 2). The pairwise comparisons indicated differences between SQUAT trial 1 with PLYO trial 1 ($P = 0.044$) and REST trial 3 ($P = 0.010$), and SQUAT trial 3 with PLYO trial 1 ($P = 0.018$) (Figure 2).

FIGURE 2 ABOUT HERE

No differences were revealed for any of the other variables. Descriptives (mean \pm SD) for P_{peak} , F_{peak} , RFD and RelF can be seen in Table 1.

TABLE 1 ABOUT HERE

DISCUSSION

The aim of the present study was to investigate PAP by examining the effect of heavy weight or plyometric exercises on repeated CMJ performance, and to compare CMJ performances between the two modes of exercise. Our findings show that heavy weight-induced PAP improved to some extent jump height compared to plyometric exercises or inactivity, as statistically significant differences were revealed in some comparisons only, while plyometric exercises presented no additional benefit to inactivity. Finally, neither heavy weight nor plyometric exercises showed any significant improvements over the course of the three trials. To the authors' knowledge, this was the first study to directly compare heavy-weight resistance and plyometric exercises in relation to PAP over repeated trials preceded by the conditioning activity.

Heavy weights have been shown to improve vertical jump performance, both in intervention (1, 17) and in acute studies (7, 29). In contrast, previous studies have reported no difference in acute CMJ performance following heavy-resistance exercise (12, 16). Indeed, in the current study no difference was revealed in CMJ jump height over the course of three trials. These results agree with the findings by Jones and Lees (12), who reported no effect of heavy resistance exercise on repeated countermovement jump performance using similar rest

intervals (12). It is worth noting that both the current study and Jones and Lees (12) employed a similar sample, with all subjects involved in sports requiring the development of explosive strength, particularly in the hip, knee extensors and ankle plantar flexors and had experience performing resistance exercises. Although such athletes may have benefited from improved motor unit synchronization (2, 15), this was not evident in the present study. Notwithstanding the lack of improvement in jump height, it is worth noting, from a practical perspective, that no impairment in performance was evident. As PAP and fatigue are simultaneously initiated following muscle contractions (20), we posit that the effect of PAP was sufficient to counteract the effect of fatigue in the SQUAT group but inadequate for enhancing performance.

One interesting finding of the study was the consistency of performance over those trials, despite no immediate effect of the SQUAT stimulus on the repeated CMJs. When the coefficient of variation (CV) was calculated (standard deviation / average x 100; 22), the SQUAT group demonstrated a much lower CV (1.3%) compared to PLYO (5.1%) and REST (4.3%). A similar displacement performance consistency was calculated from Jones and Lees (12), where the CV was 1.2%. While all the above percentages appear small, the CV needs to be considered in comparison to the performance gains expected. Significant differences in vertical jump height performance are in the region of 4% and above (14). A CV value above 4% (such as in the PLYO and REST groups), would make the interpretation of results very difficult, as any performance gain could be attributed to the variability of the measure. In addition, CV values for force (1.6%) and power (0.7%) indicate high consistency. It is suggested that in sports involving repeated performances and in which force and power are crucial, such as long jump (24), heavy-resistance exercises will assist in maintaining the required muscle output to allow the athlete to focus on the technical execution of the skill.

Plyometric exercises have been used widely as a training method to improve the efficiency of the stretch-shortening cycle as well as the muscle-tendon unit's ability to tolerate stretch loads (3). The positive effects obtained by this form of training on vertical jump performance have been established (9, 23). However, less is known about the acute effects of plyometric or power exercises as a conditioning stimulus on subsequent vertical jump performance (26). To the authors' knowledge, this is the first study to examine the effect of plyometric exercises on subsequent plyometric activity. Our study indicated that previous plyometric exercises have no impact on force and power production and that they present no additional benefit to resting between trials.

Although no previous studies have examined the effect of plyometric exercises on subsequent CMJ performance, it was hypothesised that PLYO would improve power performance, due to PAP increasing RFD in explosive activities (22). Jensen and Ebben (11) and Ebben et al (4) proposed that the concepts of plyometric intensity should be re-examined, as they reported that "high" intensity plyometric exercises, such as depth jumps, are recruiting muscle fibers as any other "less intense" plyometric exercise, such as single-leg hops. Interestingly, the vertical jump was shown to have higher muscle fiber recruitment compared to the other plyometric exercises used in their study (4). It is possible that the PLYO conditioning exercises used in the present study did not result in sufficiently high recruitment of muscle fibers to elevate the post-synaptic potentials (26). This assumption is supported by Masamoto et al (15), who used tuck jumps (high muscle fiber recruitment; 4), resulting in increased 1RM performance. However, the opposite could also hold true. The plyometric conditioning exercises could have resulted in high recruitment of muscle fibers at maximum rate, in which case PAP would offer little benefit (22). Unfortunately, in the present study as in Masamoto et al (15), electromyography (EMG) was unavailable, making it impossible to accept or refute

any of these contentions. Therefore, future studies should use EMG to assist in offering an explanation on the mechanisms by which plyometric exercises enhance subsequent strength and power performance, especially in activities that involve the stretch shortening cycle.

Finally, it is also possible that the duration of the plyometric exercises (~70 s) in the current study was too long. Vandervoort et al. (28) found that potentiation was partially suppressed by fatigue in muscle contractions over 10 s in duration, which may explain why shorter duration plyometric exercises have previously improved performance (15). The rest duration used in our study has previously been shown to be sufficient for allowing fatigue to subside (10, 25, 29). However, the duration of the conditioning exercises in these studies was lower compared to the exercise duration used in the present study, indicating that the complex relationship between duration of contractions and rest interval warrants further investigation.

PRACTICAL APPLICATIONS

Although the majority of research into PAP has recommended its use for performance enhancement, few studies have specifically investigated how such acute augmentation may be achieved in repeated performances, as those encountered in athletics competition. The results of the present study indicated that lower body power performance, as measured by CMJ height, is enhanced when preceded by three half squats at 3RM followed by five minutes rest, compared to plyometric exercises and rest. Therefore, the inclusion of sets of squats into a warm up routine prior to and during the early stages of intermittent performance may provide a beneficial alternative to traditional warm up practices. In addition, the inclusion of the above protocol in an athlete's preparation for their next performance (e.g. next jump or throw) will ensure consistent force generation across trials. The findings of the

present study may be of particular importance to athletes involved in disciplines where maximal, brief efforts are required, such as the jumping events in Track and Field, where success is a product of force and take off velocity (24). Although the extent of performance augmentation noted from the PAP mechanism is relatively small, the potential benefits that such acute improvements in performance hold to highly conditioned elite athletes should not be underestimated (5).

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FIGURE LEGENDS

Figure 1. Schematic diagram of experimental procedures. The solid squares sequence was executed three times in total for each conditioning stimulus. Condition specific warm-up or exercises refer to the inactivity (REST), plyometric exercises (PLYO), or heavy-weight squatting (SQUAT) modes of exercise.

Figure 2. Maximal displacement for each trial for the inactivity (REST), plyometric exercises (PLYO), or heavy-weight squatting (SQUAT) conditioning stimuli. Square brackets indicate paired significant differences ($P < 0.05$). Values are mean \pm SD.

TABLES

Table 1. Countermovement jump performance variables following the three different conditioning stimuli over three trials for each stimulus.

Conditioning stimulus	REST			PLYO			SQUAT		
	1	2	3	1	2	3	1	2	3
Power (W)	2254±549	2079±419	2041±372	2164±220	2174±365	2051±233	2254±391	2267±368	2236±492
Force (N)	1332±327	1240±265	1352±382	1128±294	1258±328	1294±288	1332±374	1292±347	1323±390
RFD (N/s)	401750±	462553 ±	453722 ±	372034 ±	461563 ±	360124 ±	343965 ±	346011 ±	310779 ±
	210841	231241	98521	153098	90461	69572	140920	120404	161626
Relative Force (N/BW)	1.66±0.39	1.55±0.30	1.67±0.42	1.52±0.31	1.55±0.34	1.60±0.28	1.67±0.48	1.59±0.36	1.63±0.45

Values are mean±SD. REST, inactivity; PLYO, plyometric exercises; SQUAT, heavy-weight squatting.