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Post-Activation Potentiation Following Maximal Effort, Multi-Joint, Isokinetic Eccentric Contractions

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POST-ACTIVATION POTENTIATION FOLLOWING MAXIMAL EFFORT, MULTI-JOINT,

ISOKINETIC ECCENTRIC CONTRACTIONS

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Abstract

Post-activation potentiation (PAP) is a phenomenon that can enhance muscle performance following maximal or near-maximal muscle contractions. While the effects of concentric and isometric conditioning contractions on PAP have been studied, less is known about the influence of eccentric muscle actions. This study investigated the effects of a multi-joint eccentric overload (EOL) protocol on PAP expressed through countermovement jump (CMJ) height and isokinetic peak force (PF) outcome measures. Twenty-eight recreationally trained participants (18-30 years) completed three visits in a randomized, counterbalanced design. Following familiarization, participants performed either an EOL protocol involving 2 sets of 6 maximal isokinetic eccentric contractions or a control condition (CON) involving cycling. CMJ and PF were assessed at baseline and 15 seconds, 5 minutes, and 10 minutes post-exercise. Results showed no significant condition × time interaction or main effect of condition for either CMJ or PF ($p > 0.05$). However, a significant main effect of time (collapsed across condition) was observed for CMJ ($p = 0.019$), with post hoc analyses revealing significantly higher CMJ at 5 minutes post-exercise compared to 15 seconds post-exercise ($p = 0.037$). These findings suggest that this multi-joint eccentric protocol did not effectively elicit PAP, and therefore may not be optimal for inducing acute performance enhancement. Future research should further elucidate the optimal eccentric loading parameters and contraction types for inducing PAP.

Introduction

Post-Activation Potentiation (PAP) is a phenomenon that can enhance muscle performance following a maximal or near-maximal muscle contraction (Tillin & Bishop, 2009). When utilized appropriately, PAP can enhance performance in explosive sports activities, like sprinting or high jumping for example, in either competition or training (Docherty & Hodgson, 2007). Physiologically, PAP may result from the combination of phosphorylation of myosin regulatory light chains and the increased recruitment of higher-order motor units (Hodgson et al., 2005). Phosphorylation of myosin regulatory light chains increases calcium sensitivity at the site of cross-bridge formation, leading to a greater rate of force development (RFD) (Hodgson et al., 2005). The recruitment of higher-order motor units results in greater RFD and force production due to higher postsynaptic potentials from previous contractions (Hodgson et al., 2005). Each physiological mechanism is thought to be elicited in different ways and is a major determinant in the different factors involved in the experimental protocols, as discussed later.

Maximal or near-maximal muscle contractions may lead to fatigue in addition to PAP. In the immediate aftermath of a couple of sets of maximal contractions, fatigue has been found to dominate but dissipates faster than PAP, thereby allowing PAP (if fatigue is not too great) to become dominant and enhance performance (Güllich & Schmidtbleicher, 1996). Current research efforts are focused on understanding the interplay between PAP and fatigue. Multiple factors intricately interact to modulate the magnitude and duration of the PAP versus fatigue response, with the primary aim of minimizing fatigue and maximizing PAP (Tillin & Bishop, 2009).

The relationship between PAP and fatigue is complex and influenced by factors such as contraction intensity, volume, rest periods, contraction type, and individual characteristics like strength and fiber type. While maximal-intensity contractions are optimal for inducing PAP (Tillin & Bishop, 2009), the volume should be kept low, with evidence suggesting no more than three sets should be done to minimize fatigue and maximize the PAP effect (Hamada et al., 2003). Rest periods between sets directly impact volume, and a meta-analysis by Seitz and Haff (2015) suggests that 5-7 minutes of rest produces the greatest PAP response. Additionally, stronger individuals tend to exhibit greater PAP effect sizes, potentially due to a higher distribution of type II fibers and greater resistance to fatigue (Seitz and Haff, 2015).

Both concentric and isometric muscle contraction types affect the PAP versus fatigue dynamic in different ways. One of the differences has to do with the fatigue profile of the contraction types, where isometric contractions may cause relatively more central fatigue due to the lack of blood flow to clear metabolic waste products from the contraction(s), thereby inhibiting alpha motor neuron activation and reducing neural drive (Babault et al., 2006). However, concentric contractions may lead to relatively more peripheral fatigue, where the dynamic nature of the contraction can more effectively clear the metabolites out of the muscle due to more limited restriction in the blood flow (Tillin & Bishop, 2009). Still, lactate accumulation has been proposed to alleviate peripheral fatigue, so by clearing lactate, central fatigue is reduced but peripheral fatigue likely accumulates faster (Karelis et al., 2004). Focusing on the PAP response, dynamic contractions are thought to elicit a PAP response due to increased muscle spindle firing, thereby decreasing transmission failure from Iα sensory neurons and thus increasing higher-order motor unit activation (Tillin & Bishop, 2009). In comparison, isometric contractions activate more motor neurons and may increase the percentage of myosin regulatory light chain phosphorylation (Tillin & Bishop, 2009). Both concentric and isometric contraction types have had many studies showing a PAP response and increase in performance in different types of activities (Bauer et al., 2018; Esformes et al., 2010; Esformes & Bampuras, 2013; Gahreman et al., 2020; Spieszny et al., 2022).

In comparison, fewer studies have looked at the effects of eccentric contractions when it comes to PAP. One limited area where researchers have investigated eccentric contractions is via the application of eccentric overload through flywheel devices. Beato and colleagues (2019) found a significant PAP response after a two-set flywheel eccentric overload (EOL) bout in countermovement jump and lower body isokinetic strength, 3-to-9 minutes after the exercise bout. Additional work from Beato and colleagues (2021) suggested that both medium and high-inertia flywheel squats produced similar PAP results, indicating that multiple intensity levels can produce PAP responses via flywheel exercise modality. In fact, even a single set of high-intensity flywheel EOL has produced a PAP response (Maroto-Izquierdo et al., 2020).

While several studies have examined the effects of flywheel eccentric overload contractions on PAP, there is a lack of research on the effects of pure eccentric contractions without subsequent concentric contraction. Thus, it remains unknown whether the concentric or eccentric phase of the prior studies' experimental exercise protocols was more responsible for PAP, or whether the combination of the two contraction types is necessary to induce a PAP response. Given that eccentric contractions exhibit an increased capacity for higher force output than either concentric or isometric contractions, it is possible that the eccentric-based enhanced force factor may be a primary driver of a heightened PAP response. Moreover, the combination of the dynamic attribute with eccentric mode along with the high loads may allow for an optimal scenario which allows for sufficient metabolite removal (like concentric) and higher force outputs (like isometric) to occur simultaneously. However, to address this question, the eccentric phase would need to be isolated, preferably in a multi-joint exercise model to examine the effects that an eccentric-only protocol may induce on a functional-based PAP response. Therefore, this study aimed to investigate the effects of a multi-joint eccentric-overload bout on PAP expressed through the vertical jump and eccentric (isokinetic) strength responses to gain a deeper understanding of the underlying influences on PAP.

Methods

Experimental Design

This study utilized a randomized, counterbalanced repeated-measures design to investigate the effects of an experimental (ECC) protocol involving multi-joint isokinetic eccentric contractions using a motor-driven eccentric isokinetic dynamometer (Eccentron, BTE Technologies Inc, Hanover, MD., USA) compared to a control (CON) condition involving a cycle ergometer on counter movement jumps (CMJ) and isokinetic strength (PF) as the primary outcomes. Participants arrived at the Neuromuscular Research Laboratory at Utah State University for three visits with 3-7 days in between visits, for a total of 1.5 hours. On the first visit, participants reviewed and signed the informed consent document, were familiarized with the eccentric contractions on the Eccentron machine and outcome measures. Next, participants were randomly assigned to either the CON or ECC condition, and after 3-7 days, their condition assignment was counterbalanced for visit three.

Participants

Twenty-eight participants (16 male; 12 female) volunteered to participate in this investigation. Participants were recreationally trained between the ages of 18 and 30 years. Recruitment consisted of flyers posted throughout a university campus and in-class announcements. Eligibility criteria required that participants be recreationally strength trained with the lower body, meaning they must have resistance trained legs at least once a week, but no more than twice per week for the last three months at minimum and they must have had less than five hours of aerobic exercise per week. Participants were screened for underlying health conditions that could put them at risk during exercise, and they must not have had any lower leg injuries nor surgery within the last year. Sample size needs were estimated using G*Power (version 3.0.10; Heinrich Heine Universität Düsseldorf, Germany), where it was determined that to achieve a power level of 0.8, using an effect size of 0.25 (Beato et al., 2019), and an alpha level of 0.05, a sample size of n = 22 would be required. To account for attrition, the study recruited 28 participants. The study was approved by the Utah State University Institutional Review Board, and all participants read and signed an informed consent document prior to any participation in the study.

Familiarization Session

Participants underwent a screening process involving the eligibility criteria as described above and their height and weight were measured using a wall stadiometer (Seca 216, Seca, Chino, CA) and calibrated weight scale (Tanita WB-100A, Tanita Corp., Arlington Heights, IL) with shoes off for both measurements. Assuming they met the criteria, an informed consent document was signed.

The warm-up session began with 5 minutes of stationary biking at 50 watts at 60 revolutions per minute, followed by a series of 10 body weight squats and 3 CMJs performed at a self-selected 70% effort, followed by 2 unrecorded maximal CMJ's (Spencer et al., 2023; Beato et al., 2019). Participants were instructed to perform the countermovement jumps with hands on their hips to prevent the influence of arm swing on vertical jump performance and to not flex their knee before landing (Beato et al., 2019). Participants were then seated on the Eccentron machine where the leg angle was measured with a goniometer to set the point of most extension at ~30 degrees. Participants then performed 2 submaximal effort sets of 6 reps per leg at a self-selected 30-50% effort, followed by 70% and ended with a maximum effort set, with 2-minutes rest between sets. Isokinetic speed was set to 23 reps per minute (Spencer et al., 2023).

Sessions 2 and 3

The warm-up followed the same procedures described in the familiarization session, minus the initial 30-50% set on the Eccentron. Two minutes following the warmup, participants performed baseline testing consisting of 2 maximal CMJ's using a Just Jump Mat (Just Jump Technologies, Huntsville, AL) and 2 maximal isokinetic reps on the eccentron. The participants were randomized into either the ECC or CON conditions. For the ECC, participants performed a bout of two sets of eccentric maximal voluntary contractions (MVCs) on the Eccentron which involved 2 sets of 6 MVCs per leg (12 total), done in an alternating, consecutive manner, with 2-minutes rest between sets. For the CON condition, participants performed 5 minutes of stationary cycling at 60 revolutions per minute at 1 watt/kg of body weight (Beato et al., 2019). Upon completion of the eccentric protocol or stationary cycling, a timer was started and run for the duration of the follow up protocol.

Follow up testing was conducted at 15 seconds, and 5-, and 10-minutes post-exercise using the same procedures as the baseline tests. Next, participants were scheduled for the third and final session during which they performed the other condition.

Data acquisition

The CMJ height values from the Just Jump Mat were recorded manually. All raw force data (V) for maximal eccentric strength measures were collected using a data acquisition system (MP150WSW; Biopac Systems, Inc., Santa Barbara, CA, USA). Force data were sampled at 2000 Hz and processed offline with custom-written LabVIEW software (LabVIEW 2021, National Instruments, Austin, TX). The force signal was filtered using a fourth-order, zero-phase Butterworth filter at a low pass frequency of 50 Hz (Thompson et al., 2017). The highest value attained from the isokinetic eccentric MVCs was used for subsequent analyses.

Statistical Analyses

Statistical analyses were conducted via SPSS software (version 25; IBM SPSS, Inc., Chicago, IL, USA) and utilized a two-way repeated measures analysis of variance (ANOVA) to test for differences between conditions (ECC × CON) as well as across four time points (baseline × 15 s × 5 min × 10 min). Descriptive statistics were reported as mean ± standard deviation and significance was determined using an alpha level of $P < .05$.

Results

All data are presented as means (SD) in Table 1. For CMJ, there was no significant condition × time interaction ($F(3, 81) = 0.417$, $P = 0.741$) and no main effect for condition ($F(1, 27) = 0.239$, $p = 0.629$). However, a significant main effect of time was observed ($F(3, 81) = 4.497$, $P = 0.019$), with post hoc analyses revealing that CMJ was significantly higher at time point 3 (5 min post-exercise) compared to time point 2 (15 s post-exercise) ($P = 0.037$). For PF, there was no significant condition × time interaction ($F(3, 81) = 0.273$, $P = 0.844$) and no main effect for condition ($F(1, 27) = 1.215$, $P = 0.280$) or time ($F(3, 81) = 2.136$, $P = 0.102$).

Table 1. Mean (SD) for counter movement jump height and peak force across conditions and time points.

Variable	Control	Eccentric
Baseline CMJ (cm)	44.35 (9.75)	44.29 (9.40)
15 s Post CMJ	43.79 (9.73)	43.89 (9.27)
5 min Post CMJ	44.65 (9.75)	44.81 (9.70)
10 min Post CMJ	44.22 (10.01)	44.53 (9.48)
Baseline PF (N)	2450.82 (390.48)	2391.06 (444.95)
15 s Post PF	2453.80 (383.34)	2424.82 (429.92)
5 min Post PF	2409.11 (402.68)	2336.66 (417.57)
10 min Post PF	2408.96 (407.79)	2365.88 (456.72)

Note: CMJ = counter movement jump; PF = Peak Force; N = Newtons

Discussion

The primary finding of this investigation was that two sets of six maximal isokinetic eccentric contractions failed to elicit a PAP response at any time period for CMJ or PF, nor any significant differences between CON or ECC conditions.

While the current study did not find a significant PAP effect following an eccentric-only conditioning protocol, other studies have investigated the effects of EOL exercises on PAP using similar protocols. Beato et al. (2019) examined the effects of EOL flywheel half-squats on CMJ performance and lower-limb muscle strength. They found significant improvements in CMJ height, peak power, and peak force at various time points between 1- and 9-minutes post-exercise, as well as increased quadriceps and hamstrings isokinetic strength. However, their EOL protocol utilized a lower intensity (0.029 kg·m^{-2} flywheel inertia) compared to the maximal eccentric load used in the current study, which may partially explain the discrepancy in findings.

Similarly, de Keijzer et al. (2020) investigated the effects of different EOL exercise volumes on PAP, comparing the effects of 1, 2, and 3 sets of flywheel half-squats on CMJ and long jump performance. They found that 2 and 3 sets of EOL exercise resulted in significant PAP effects on both CMJ and long jump performance at 6 minutes post-exercise, while a single set did not induce PAP. Although their study also utilized a lower intensity (0.029 kg·m^{-2} flywheel inertia) and a different exercise modality (flywheel half-squats involving both eccentric and concentric phases) compared to the isolated eccentric actions used in the current study, the findings nonetheless highlight the potential role of EOL exercise volume in modulating PAP responses.

Although the reason for the lack of a PAP response in this investigation is unknown, one potential explanation for the lack of a PAP response in this investigation is that the intensity of the eccentric conditioning contractions may have been too high relative to the loads used in previous PAP studies, which typically base their loads on concentric 1RM. Eccentric muscle actions can produce 20-60% greater force compared to concentric actions (Franchi et al., 2017). The present study utilized a 100% 1-RM load based on maximal eccentric force, which would equate to approximately 120-160% of one's concentric 1-RM. In contrast, many PAP studies use loads ranging from 60-90% of concentric 1RM. For example, Bauer et al. (2019) used 60% and 90% of concentric 1RM in a back squat protocol and found PAP effects on CMJ performance. Similarly, Seitz and Haff (2016) reported in a meta-analysis that PAP effects were elicited using loads ranging from 60-84% of concentric 1RM. While the flywheel studies by Beato et al. (2019)

and Beato et al. (2021) did apply eccentric overload, the inertial loads used were likely lower than the 100% eccentric 1RM used in the current study. Consequently, the high intensity eccentric contractions used in our protocol, when compared to the lower intensities typically used in PAP studies based on concentric 1RM, might have induced excessive fatigue, counteracting any potential potentiation effects.

In connection with the relatively heightened intensity is the resulting higher volume of the eccentric conditioning contractions here, as perhaps compared to other PAP investigations. Although our protocol utilized a similar number of sets and repetitions (2 sets of 6 reps) as previous studies that have demonstrated PAP effects (de Keijzer et al., 2019), the relatively higher intensity (100% eccentric 1-RM) from the eccentric actions would have resulted in greater overall load/volume. Tillin and Bishop (2009) suggest that too high of volumes of conditioning contractions can lead to excessive fatigue, which may counteract the potential benefits of PAP. Indeed, getting the load/volume in the optimal balance for eliciting PAP is challenging, as fatigue may overcome potentiation when the optimal load/volume is exceeded. For instance, de Keijzer et al. (2019) reported that 2 sets of flywheel eccentric overload exercise were required to induce PAP effects on countermovement jump and long jump performance, while a single set was not enough. However, it is important to note that the intensity used in their study (0.029 $kg \cdot m^{-2}$ flywheel inertia) was likely lower than the 100% eccentric 1-RM used in our protocol. Consequently, the combination of higher relative intensity from the eccentric-based training intensities used, and multiple sets in our study might have resulted in an excessively high volume/load, leading to fatigue that overshadowed any potential PAP effects.

The underlying mechanisms of PAP may also have been a key factor for the present findings resulting from the eccentric-only protocol. One of the proposed mechanisms of PAP is the phosphorylation of myosin regulatory light chains (RLCs), a process that requires calcium release from the sarcoplasmic reticulum (Sweeney et al., 1993). However, eccentric contractions have been shown to have unique calcium dynamics and have been associated with a lower energy cost and distinct neural activation strategies compared to concentric contractions (Franchi et al., 2017). Consequently, the lower calcium transient during eccentric contractions could lead to reduced phosphorylation of myosin RLCs, thereby attenuating the PAP response. Therefore, it is possible that the unique calcium dynamics and excitation-contraction coupling responses that are specific to eccentric-only contractions may explain the lack of PAP effect observed in the present study. However, more research is needed to investigate these proposed mechanisms regarding eccentric-based protocols and PAP.

Another potential explanation for the lack of PAP effect in the present study is the possibility of reduced firing rates of high-threshold motor units following the maximal eccentric contractions. Farup et al. (2016) demonstrated that the firing rates of later recruited, high-threshold motor units were significantly reduced following maximal eccentric exercise, while the firing rates of early- and mid-recruited motor units remained unchanged. Similarly, Balshaw et al. (2017) found a decline in the firing rates of high-threshold motor units following eccentric overload contractions, despite no changes in maximal voluntary contraction force. These findings would corroborate this theory such that eccentric contractions, particularly when performed at high eccentric intensities and overload as in the present study, may selectively impair the firing rates of high-threshold motor units. Given that high-threshold motor units are preferentially recruited during high-force contractions and are associated with fast-twitch muscle fibers, a selective reduction in their firing rates following eccentric exercise could potentially attenuate the PAP response. The attenuation of high-threshold motor unit firing rates following eccentric actions (Farup et al., 2016; Balshaw et al., 2017) could potentially explain the lack of a PAP effect in the current study, as the eccentric-only preconditioning protocol may have selectively impaired the firing rates of the motor units most responsible for explosive force production. However, further research is needed that investigates these motor unit-based mechanisms with high intensity eccentric-only protocols.

Another possible explanation for the lack of PAP in the present study is that eccentric muscle actions are known to cause muscle damage, particularly at high intensities or volumes, which can lead to decrements in force production (Howatson & van Someren, 2008; Proske & Allen, 2005) In the present study, although the eccentric conditioning protocol involved a relatively low volume (2 sets of 6 repetitions), the high relative intensity (100% of eccentric 1RM) might have induced some level of muscle damage. This damage, even if minimal, could have contributed to the lack of PAP effect observed. Muscle damage can impair force transmission and excitation-contraction coupling (Proske & Morgan, 2001), potentially offsetting any potentiating effects of the conditioning contractions. However, it is important to note that the extent of muscle damage and its impact on performance can vary depending on factors such as the exercise protocol, muscle group, and individual characteristics (Nosaka & Aoki, 2011). Given that our protocol involved a relatively low volume and that participants were resistance-trained individuals, the role of muscle damage in the observed outcomes would be expected to be limited, although it may have still been minimally present, enough to have a small PAP attenuating effect. Nevertheless, to examine this plausible mechanism, future studies could directly assess markers of muscle damage following similar eccentric conditioning protocols to better understand its potential influence on PAP responses.

While the present study focused on the PAP response following isolated eccentric conditioning contractions, it is worth noting that most previous studies investigating eccentric exercise have utilized protocols involving both eccentric and concentric actions, such as flywheels or the lowering and lifting phases of a squat or bench press (Esformes et al., 2010). Therefore, it is possible that the absence of a subsequent concentric contraction following the eccentric conditioning contractions in our protocol could have influenced the PAP response. However, to our knowledge, no other studies have used a protocol completely lacking the concentric contraction. Thus, this study provides an important contribution to the literature by examining the PAP effects from an eccentric-only conditioning protocol, without any influence of the concentric muscle action. Future research may directly investigate the potential differences between concentric and eccentric-only protocols to shed more light on the role that contraction type plays on PAP as well as to better understand the optimal contraction type and sequence for inducing PAP.

The only statistically significant finding in this study was a main effect of time (collapsed across groups) on CMJ performance, with post hoc analyses revealing that CMJ height was significantly higher at 5 minutes post-exercise compared to 15 seconds post-exercise. Various factors could potentially influence this time-dependent change in CMJ performance, such as the recovery of the stretch-shortening cycle, the dissipation of muscle fatigue, or changes in neuromuscular activation patterns. It is important to note that this time effect was observed regardless of the conditioning protocol (ECC or CON), suggesting that the recovery process itself, rather than the specific intervention, may have been the primary driver of the observed improvement in CMJ height. However, further research is needed to elucidate the specific mechanisms underlying this time-dependent effect on CMJ performance in the context of EOL protocols.

The present investigation had some limitations that are noteworthy. First, the study involved a relatively small sample size of recreationally trained individuals, which may limit the generalizability of the findings to other populations, such as highly trained athletes or sedentary populations. Second, the study only examined the acute PAP response to a single eccentric conditioning protocol; future research should investigate the effects of different eccentric loading parameters and training durations on PAP (for example, a future study could look at the effects of a single set of 6 maximal eccentric contractions rather than 2 sets). Third, the study did not directly assess markers of muscle damage or fatigue, which could have provided additional insight into the mechanisms underlying the observed lack of PAP effect. Despite these limitations, the present study provides valuable insights into the PAP response to maximal isokinetic eccentric contractions and highlights potential areas for future research.

In summary, the present study found that two sets of six maximal isokinetic eccentric contractions failed to elicit a PAP response in recreationally trained individuals. Several potential explanations for this lack of PAP effect include the high relative intensity and, consequently, greater load/volume of the eccentric conditioning contractions as compared to concentric-focused studies, the unique calcium dynamics and excitation-contraction coupling responses that are inherent to eccentric muscle actions, potentially reduced firing rates of high-threshold motor units following maximal eccentric exercise, and the potential role of muscle damage. In practice, it does not appear that performing multi-joint eccentric conditioning repetitions has any benefit for improving functional (VJ) or strength-based measures in the minutes that follow the protocol.

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