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The Effects of Acute Bilateral and Unilateral Set Protocols on Muscle Power and Rate of Force Development

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Abstract

Post activation potentiation (PAP) is used to improve the force generating capacity of skeletal muscles. However, no studies have examined if there is a difference in PAP response when comparing a unilateral versus a bilateral conditioning exercise. This is important because differences exist in muscle activation when comparing unilateral and bilateral exercises. Therefore, the purpose of this investigation was to determine if a unilateral exercise would cause a different PAP response compared to a bilateral exercise. Ten recreationally trained males participated (mean ± SD; age = 21.9 ± 2.1 yrs; body mass = 83.3 ± 10.5 kg; height = 1.8 ± 0.1 m; BMI = 25.8 ± 3.2; percent body fat = 14.8 ± 3.5%). Following a familiarization period and baseline strength testing all subjects completed 3 trials: unilateral, bilateral and control. Each trial consisted of a conditioning activity (4 reps at the 5RM load) followed by a maximal voluntary isometric leg extension contraction (60° knee extension) 7 minutes after finishing the conditioning activity. Neither conditioning activity (unilateral or bilateral squat) resulted in an increased peak torque value expressed in absolute or relative values as compared to control. Interestingly, following both conditioning activities, there was an increased time to reach half peak torque compared with the control trials ($P < 0.05$). Our results demonstrated that neither conditioning activity prior to a maximal voluntary isometric contraction caused a PAP response. However, both conditioning activities appeared to cause residual fatigue.

Introduction

The ability of a muscle to generate force is important for general health. Post activation potentiation (PAP) is an intriguing training approach that has been shown effective for improving the force generating capacity of skeletal muscles [1]. By definition, PAP has been described as an acute enhancement in the force-generating capacity of skeletal muscle, as the result of a biomechanically similar “conditioning action” [2]. It is believed that following the conditioning action, both fatigue and potentiation exist simultaneously, and during the recovery period, fatigue dissipates at a faster rate than the potentiation response. After the recovery period, it is postulated that a brief window of opportunity exists to capitalize on the potentiation effect [2-4]. Potential mechanisms that have been linked to the exploitation of PAP are the recruitment of higher order muscle units, an increased rate of regulatory myosin light chain phosphorylation resulting in a more efficient muscle contraction, and acute changes in the muscle angle of pentation. Exploitation of the PAP response has been attempted within resistance training settings [4-6] and in pre-competition warm-ups [7,8]; however, presently a dearth of data exist examining the PAP response within clinical settings [9].

Even with the increasing popularity in research and application of PAP inducing training protocols, numerous gaps still exist in the literature. For example, it is unknown what is the optimal muscle action (static *vs.* dynamic) to maximize the PAP response in a skeletal muscle. Currently, evidence supports the use of static conditioning actions over dynamic [10], whilst other research has demonstrated the opposite with dynamic conditioning actions being more effective than static [11]. Additionally, there is evidence in the literature that supports the notion that an individual’s physical characteristics influence their ability to capitalize on PAP [2]; however, an intriguing and yet unexplored area within this field is whether a difference in PAP response occurs when comparing a unilateral versus a bilateral conditioning exercise. This is important because unilateral exercises are often prescribed by clinicians as part of the rehabilitation process to improve strength and power in both general and athletic populations. Currently, there is a preponderance of evidence demonstrating that differences exist in muscle activation when comparing unilateral and bilateral exercises [12].

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The apparent difference in strength between unilateral and bilateral exercise has been coined "the bilateral deficit" (BLD) and it has been well documented in the literature over the years [13,14]. Many proposed mechanisms underlie the BLD with a multitude of factors (e.g., muscle groups examined, contraction types used, subject training status, etc.) contributing to its presence and magnitude [12]. Nevertheless, unilateral exercises appear to have the potential to recruit a greater number of motor units and thus a greater percentage of muscle mass, when compared to bilateral exercises. Hypothetically, this enhanced recruitment could lead to a greater PAP response when used as a conditioning activity. Importantly, unilateral exercises can obtain maximal activation using a lighter absolute load, which may have clinical implications for PAP producing protocols [9]. For example, a clinician could rehabilitate an athlete and take advantage of the PAP response by using unilateral exercises with those athletes that may not be able to tolerate the heavy loads typically used in bilateral PAP producing protocols.

Therefore, the purpose of this investigation was to determine if an intensity matched unilateral dynamic conditioning exercise would cause a different PAP response compared to a bilateral dynamic conditioning exercise on subsequent muscle contraction performance. This experiment is important for numerous reasons. First, if a difference in the PAP response appears between the different conditioning exercises (i.e., unilateral *vs.* bilateral), then practitioners would be wise to incorporate more of the movements that produce the greater response. Secondly, if there is no difference, this is very practical information, since many times adequately loading a bilateral movement is not appropriate in a clinical setting (i.e., 5RM back squat); therefore, a client or patient could more reasonably overload their muscles unilaterally in a clinical setting. Consequently, clinicians who aim to increase strength and power in individuals they are rehabilitating could use appropriately loaded unilateral exercises more than under-loaded bilateral exercises (e.g., body weight unilateral squats *vs.* body weight bilateral squats). Therefore, it stands to reason, that unilateral conditioning exercises may serve a greater role in enhancing the subsequent PAP response in a rehabilitation context. However, to our knowledge, this has not been carefully examined.

Methods

Experimental design

Within-subjects repeated measures design was used to determine the acute effect of bilateral versus unilateral post-activation potentiation (PAP) protocols on lower-body muscle function. Ten recreationally trained males completed testing sessions to assess how the two different PAP protocols affected peak force and rate of force development (RFD) during an isometric knee extension test. Testing sessions were executed in a randomized order, and each session was separated by 3-5 days.

Subjects

Informed consent was obtained from all participants prior to the start of the study, and approval was granted by the Sonoma State University's Institutional Review Board. Ten recreationally trained males participated in this investigation (mean ± SD; age = 21.9 ± 2.1yrs; body mass = 83.3 ± 10.5kg; height = 1.8 ± 0.1 m; BMI = 25.8 ± 3.2; percent body fat = 14.8 ± 3.5%). Height was measured using a stadiometer (Seca 220, Seca Corporation, Hamburg, Germany). Weight was measured using a calibrated digital scale (Seca 769, Seca Corporation, Hamburg, Germany). Body composition was measured noninvasively using bioelectrical impedance (Body stat® 1500 MDD; Body stat Ltd, Douglas, Isle of Man, UK) following manufacturer's instructions.

All subjects had been participating in a resistance exercise program for at least 1 year before the current investigation and were able to perform a parallel back squat with an external load of no less than one and a half times their body mass. All participants were free from injury during the time of the study and were asked to cease all other lower body resistance training starting 24 hours prior to the first session through completion of the study. Participants were asked to refrain from caffeine and alcohol intake 24 hours prior to attending a testing session, and to maintain their normal diet throughout the study. Subjects arrived to their testing sessions following an overnight fast.

Procedures

Although all participants regularly participated in resistance training, a two to four week familiarization program was implemented to educate and reinforce correct squat technique and reduce variability in isometric force production. The purpose of the familiarization program was not to develop strength but to assess and reinforce appropriate exercise technique as well as decrease variability in key dependent measures (e.g., maximal voluntary isometric force and time to reach peak torque (i.e., rate of force development).

Following the familiarization period, all participants attended two sessions to determine their five repetition maximum (5RM) bilateral back squat (2-leg squat) and 5RM unilateral back squat (1-leg squat) in a randomized order using previously establish guidelines and methodologies (see protocol below) [5]. Sessions were separated by a minimum of 72 hours to minimize fatigue from the previous session, and occurred at the same time day to account for diurnal fluctuations in the explosive force generating capacity of muscle [15]. On days were subjects completed their 5RM testing, they were also exposed to the isometric testing on the dynamometer (see protocol below).

After subjects' established their 5 RM in the 1- and 2-leg squat, they returned to the lab for three subsequent experimental trials, separated by at least 48 hours and after an overnight fast. These trials consisted of either a conditioning activity (1- or 2-leg squats) or a control trial (no conditioning activity) prior to a maximal voluntary isometric leg extension contraction. The order of trials were randomly assigned and all subjects completed each of the three trials (1-leg squat, 2-leg squat, and control). Testing sessions commenced with a standardized warm-up, which consisted of cycling at 50 watts on a stationary ergometer (Monark 828E, Vansbro, Sweden) for five minutes. Thereafter, subjects performed one set of 10 repetitions of the squat(either 1- or 2-leg, depending upon trial) at 50% of the established 5RM followed by three minutes of rest; one set of 4 repetitions at 70% of 5RM, followed by three minutes of rest; one set of 2 repetitions at 80% of 5RM followed by three minutes of rest. After the final three minute rest, participants completed the main intervention set or "conditioning activity", which consisted of one set of four repetitions using the established 5RM (i.e., 4 reps at 5RM) for the given squat condition (i.e., 1-leg or 2-leg). Thereafter, participants were positioned onto the dynamometer and waited until 7 minutes elapsed following the last repetition of the squat before producing a maximal voluntary isometric leg extension contraction (see protocol below). The rest interval between completion of the conditioning activity and the isometric contraction was chosen to optimize the

Table 1: Results of 5RM testing for both 1- and 2-leg squats.

5 RM 2-leg Squat (kg)	5RM as % BM	Estimated* 1RM (kg)	Estimated 1RM as % BM	5 RM 1-Leg Squat (kg)	1-leg as % 2-leg Squat
117.7 ± 34.6	140 ± 30	138.5 ± 40.7	160 ± 30	77.7 ± 18.9	67.3 ± 8.6
*Estimated 1RM was calculated by assuming 5RM squat was equal to 85% of 1RM.					
BM = Body mass (kg); RM = Repetition Maximum.					

PAP response within our subject population (recreationally trained), based upon the evidence demonstrated within the literature [16].

Note, for the control trial, subjects rode the stationary ergo meter for 5 mins and then walked/stood around the lab for 17 mins and 30 seconds. They completed their maximal isometric contraction after the 17 min and 30 second rest. This timeframe was selected based upon preliminary testing demonstrating this time interval was on average how long it took subjects to complete all of the warm-up sets, the intervention set and rest 7 mins; thus, the time frames were equivalent between all trials from when the subjects completed the 5 min cycle warm up to when they completed the isometric contraction.

Measurements

Maximal isometric leg extension contraction: subjects performed a maximal voluntary unilateral isometric knee extensor action at 60° of knee extension (0° = full extension) with their dominant leg on a calibrated dynamometer (Humac/Norm Testing and Rehabilitation System, Computer Sports Medicine, Inc., Massachusetts, USA). Subjects were upright in a seat with their hands securely grabbing the seat handles. Moreover, a seat belt with shoulder straps helped secure the subject into these at. The testing position of the subject was in accordance with the Humac®/Norm User's Guide (Humac®/Norm Testing and Rehabilitation System, Computer Sports Medicine, Inc., Stoughton, Massachusetts, USA. 2006).The instruction to contract as quickly as possible preceded each contraction [17] and each contraction lasted 5 s. Unilateral isometric leg extension force-time curves, maximal force, and maximal rates of force development (RFD; time to half peak torque) were measured on the dynamometer. The maximal voluntary contraction (MVC) was defined as the highest value of torque recorded during the entire isometric contraction [18]. RFD was calculated according to Viitasalo et al. [19].

5RMsquat: Subjects had both their 1- and 2-leg squat 5RM determined because this served as the weight used for the conditioning activity. 5RM testing occurred during the first familiarization session using a Smith machine (Cybex International, Model 5341-001-97, Owatonna, Minnesota, USA). All participants had a history of resistance training and thus had a rough estimate of their current 1RM for 2-leg squat. Therefore, we used an estimate (~80-85%) of their 1 RM squat for their first attempt at a 5RM. Note, participants were permitted to use weightlifting belts as they required. If a belt was used during 5RM testing, the belt was also used during the intervention trials. Moreover, all subjects were required to use the same footwear for their trials that they wore during their 5RM testing trials.

All participants performed an identical warm-up prior to their first 5RM tests. Subjects completed three warm-up sets with three minutes of rest between sets using the following repition and loading scheme: 10 repetitions at an estimated 60% of 5RM, 5repetitions at an estimated 80% of 5RM, and 3 repetitions at an estimated 90% 5RM. Three minutes after the final warm-up set, participants attempted their first 5RM. For the 2-leg squat, a lift was deemed to be successful if the subjects could descend until the inguinal fold was lower than

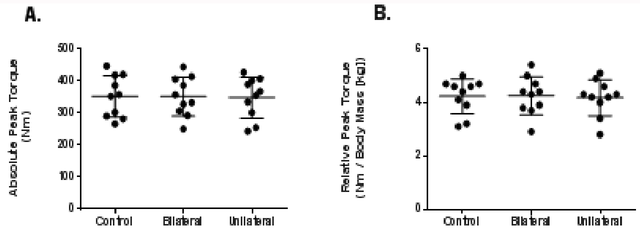

Figure 1: Maximal voluntary isometric peak torque values following 2-leg (bilateral) and 1-leg (unilateral) conditioning exercises expressed in (A.) absolute units (newton-meters [Nm]) and (B) relative units (Nm/body mass [kg]). Values are expressed as mean ± SD.

the patella and rise without help as per the International Power lifting Federation rules (International Power lifting Federation 2002). If optimal depth was not obtained, feedback was provided to decrease the squat depth. If subjects failed to reach the desired squat depth on three repetitions, then the attempt was considered a failure. If subjects were successful, the weight was increased 5-10% based upon their feedback, until they could not successfully lift the weight through the required range of motion for a full five repetitions. A 3-5 minute rest was provided between each attempt, and all participants reached their 5RM within five attempts.

For the 1-leg squat, the same testing progression with weight percentages and rest intervals as outlined above was followed. The 1-leg squat form followed guidelines as previously described [20]. However, since many subjects did not have an estimate of their 1RM 1-leg squat, we used a percentage of their estimated/self-reported 1RM for the 2-leg squatto obtain appropriate loads to use for the warm-up sets. Lastly, foot position was recorded for both the 1- and 2-leg squats based on a numbered grid marked on the floor to ensure that positioning was consistent between all testing and intervention trials.

Statistical analysis

Statistical analysis and graphs were completed using Sigma Stat® and Graph Pad Prism® 6.07. Data were analyzed with a one-way repeated measures analysis of variance (ANOVA). Holm-Sidak post hoc tests were performed when significant main effects were present. Significance was established a priori at $\alpha < 0.05$. Values are presented as means ± standard deviations (SD).

Results

5RM testing

Subjects were required to have participated in a resistance exercise program for at least 1 year before the current investigation and be able to perform a parallel back squat with an external load of at least one and a half times their body mass. The current investigation utilized a smith machine for testing purposes to maximize safety and repeatability of set-up and squatting form. Results of subjects' 5 RM testing is shown in Table 1. We estimated our subjects' 1RM based upon the assumption that a 5RM equals roughly 85% of each subject's

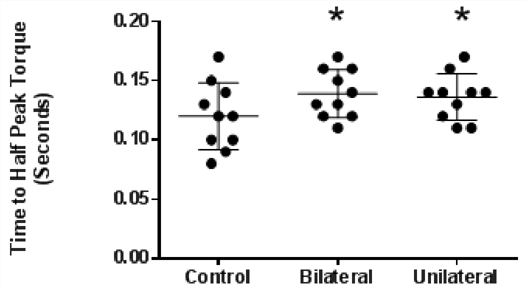

Figure 2: Time taken to reach half peak torque during maximal voluntary isometric contraction following 2-leg (bilateral) and 1-leg (unilateral) conditioning exercises. Values are expressed as mean ± SD. *statistically significant difference from control (p <0.05).

1RM. The 1RM estimate was 138.5 ± 40.7 kg, which when expressed as a function of body mass, represented 160 ± 30% body mass. Thus, even with a smith machine, which some athletes may be unfamiliar with, each subject was still able to squat one and a half times their body mass. Based upon these numbers, we would classify our subjects as recreationally trained individuals and not necessarily well trained athletes (i.e., NCAA competitors) [16]. Of note, subjects' 5RM on the 1-leg squat represented 67.3 ± 8.6% of their 5RM for the 2-leg squat (Table 1).

Maximal voluntary isometric leg extension force. Following the conditioning activity, either the 1-leg or 2-leg squat, subjects completed a maximal voluntary isometric leg extension contraction. Interestingly, neither conditioning activity (1- or 2-leg squat) resulted in an increased peak torque value expressed in either absolute (Figure 1A) or relative values (Figure 1B).

Interestingly, following the conditioning activities, there was a statistically significant (P <0.05) increased time to reach half peak torque compared with the control trials following both the 1- and 2-leg conditioning activities (Figure 2).

Discussion

Post activation potentiation (PAP) is a rapidly burgeoning area of research in the field of strength & conditioning. However, an unexamined area in this field pertains to whether a differential PAP response may occur when comparing intensity-matched unilateral and bilateral exercises. This question is important because typically the force produced using bilateral exercises is less than the summed force of the individual limb contractions (i.e., the force generated during a bilateral bicep curl is less than the summed force of a unilateral biceps curl), which has been termed the "bilateral deficient" [12]. Of note, unilateral exercises appear to increase motor unit recruitment and thus could be hypothesized to augment the PAP response. Since unilateral exercises utilize less overall resistance, these exercises may be more feasible in both field and clinical settings. Therefore, examining the PAP response following bilateral and unilateral exercises has great practical utility. Our results demonstrated that neither conditioning activity (bilateral or unilateral squats) prior to a maximal voluntary isometric contraction caused a PAP response. Additionally, both conditioning activities appear to cause residual fatigue. The following sections will elaborate on these results.

Bilateral deficit

Using isometric and isokinetic movements in both upper and lower limbs, a plethora of evidence exists demonstrating the bilateral deficient (BLD) [12]. However, there is a dearth of investigations examining the BLD using more functional movements such as the squat. To this end, many investigations have examined the BLD using leg press machines (i.e., combined hip and knee extension) [21] or counter-movement jumping [22,23].

Firstly, our investigations ought to see if the BLD existed when a bilateral squat was compared to a unilateral squat. Note, many different terms are used in the literature to characterize (or label) squats that predominantly utilize one leg (e.g., single-leg squat, split squat, lunge, etc.). The present investigation implemented a "modified single-leg squat" [20]. From our pilot testing, this squat variation was chosen for three major reasons: 1) the subjects could quickly learn and consistently execute this variation through the required full range-of-motion (i.e., this variation is easier than true single-leg squats were stability and mobility restrictions would prevent subjects from attaining full range of motion), 2) for safety purposes, this variation was able to be performed within the confines of the smith machine to allow adequate spotting, and 3) most significantly, this variation closely replicated the movement pattern of the leg as observed during a bilateral squat. Additionally, to control for possible differences in the movement patterns and moments of force at each joint between the two types of squat in this study, the subjects practiced performing the 1-leg squat with the lead knee positioned above the toes similar to the degree of anterior translation of the knee performed during the 2-leg squat.

Importantly, our results demonstrated a BLD when comparing the bilateral to unilateral squat, which replicated findings observed when using leg press or jumping movements to examine the BLD [21]. The 5RM for the 2-leg squat was 117.7 kg while the 5RM for the 1-leg squat was 77.7kg, which represented 67% of the weight used during the 2-leg squat (i.e., more than 50% of the 2-leg 5RM).

When using the same 1-leg squat variation, a previous investigation demonstrated that subjects display greater EMG activity in the gluteus medius and hamstrings during the 1-leg compared with greater quadriceps activity during the 2-leg squat [20]. The lower quadriceps activity during the 1-leg squat is likely a result of the ability to support a portion of the load on the trail leg to assist knee flexion and extension during the 1-leg squat. Higher quadriceps activity during the 2-leg squat could have also resulted, in part, from the potential to produce higher knee-extension force with the more stable exercise, indicated by less knee-valgus motion [20]. Note, while more quadriceps activity would thought to have occurred during the 2-leg squat, and therefore caused a greater PAP response on a subsequent isometric knee extension, which predominantly utilizes the quadriceps muscles, there were no differences observed regarding a PAP response following either the 2-leg or 1-leg squat variations used as conditioning activities (Figure 1). This may have been a result of residual fatigue being present before the PAP could have taken place. More will be said about this in the subsequent section.

PAP Protocol parameters

When examining the PAP literature, the results may appear equivocal regarding the various components in the protocols used (e.g., activity type, rest intervals, subject characteristics, etc.), however, many important trends have emerged. For example, the preponderance of evidence demonstrates that subject training state, rest intervals following conditioning activities and the numbers of sets of the conditioning activity play key roles in the subjects' sub sequent PAP response [16]. Therefore, the current investigation sought to maximize the chances of obtaining a PAP by following these guidelines. Since we were recruiting trained individuals (*vs.* untrained or athletes [16]), we chose to use a moderate intensity resistance load (moderate = 60-84% 1RM (16)) and used a moderate rest period length (7-10 mins [16]) following the conditioning activity prior to the testing measurement. The conditioning activity consisted of completing 4 repetitions at 100% of a pre-tested 5RM value using a 1-leg or 2-leg squat. The 4 reps at 5RM was a load that seemed appropriate to reach the moderate (60-84% 1RM) load that was desired. We chose to not have the subjects go to failure to minimize the chances of fatigue overriding the PAP. Interestingly, this load and rest interval was not able to elicit any greater increase in peak torque when expressed in absolute units or relative to body weight (Figure 1A, B). Moreover, this conditioning activity appeared to still cause residual fatigue in the subjects due to the increased time to reach half peak torque (Figure 2). This result was somewhat surprising based upon the strong support for using this protocol (loading pattern and rest interval) in the literature.

Previous investigations have utilized a 5RM back squat as a conditioning activity 5 minutes prior to a counter jump movement and demonstrated a PAP response [24]. Therefore, based upon these results and using an less rigorous conditioning activity (4 reps at 5RM in the current study *vs* 5 reps at 5RM [24]) with a longer recovery period (7 mins *vs.* 5 mins) was thought to be able to induce a PAP; however, no enhancement was observed following the conditioning activity. Furthermore, a decrease in the rate of force development still existed.

Interestingly, a previous investigation's results may shed some light on the current study's results. A previous investigation demonstrated a 15 minute lag in PAP response following bilateral squatting prior to knee isometric contractions [25]. Gilbert et al. [25] had subjects complete 5 total repetitions at their predetermined 1RM with each single repetition being separated by 5 mins. Following this conditioning protocol, these investigators examined the time course of maximal force development and rate of force development for 60 minutes. Their results demonstrated that the conditioning activity did not increase maximal force at any time points; however, following an initial decrease in rate of force development (at 2 mins post activity), then no change in rate of force development (at 10 mins), they found at 15 and 20 minutes after the activity, a significant increase in the rate of force development occurred which then returned to baseline 60 mins after the activity [25]. Based upon these results, one could speculate that the PAP response (increased rate of force development and not increased maximal force) may have been observed in the current investigation if further contractions were completed. In the present investigation, all of our subjects completed a second isometric contraction 3 minutes following their first isometric contraction (10 minutes post conditioning activity). Of note, there was no increase in force production or increase rate of force production with this contraction (data not shown). Similarly to Gilbert et al. [25], a previous isometric contraction does not seem to act as a robust enough stimulus to create a potentiation in the skeletal muscle by itself. Lastly, it has been demonstrated that stronger athletes will have a greater incidence of PAP responses [16]. Therefore, we completed further analysis to see if the strongest subjects (i.e., those with the highest absolute or relative 5RM squatting values) were those subjects that had increased peak torque values following the conditioning activity compared to their control trials. Unfortunately, no such trends were found in the data (data not shown).

Practical applications

Whilst PAP has been shown to improve performance related aspects such as power and speed in highly trained athletes, less is understood about its clinical applications [4]. The results of this investigation indicate that for exploitation of PAP in a clinical setting using unilateral exercises to be successful, better understanding of programming variables is needed. Clinicians who aim to improve the force generating capacity of individuals who are rehabilitating from injury with the implementation of PAP protocols should not attempt to utilize that similar loading and rest parameters that have been shown to be effective in highly trained athlete populations. Instead, it would behoove clinicians to focus on more conventional methods of strength and power development.

Summary and Conclusion

In summary, this investigation is the first to study the differences in the PAP response to intensity matched unilateral and bilateral exercises. Our results revealed that our conditioning activity (4 repetitions at a 5 RM) did not lead to a subsequent PAP response on a maximal voluntary isometric leg extension contraction 7 minutes after cessation of the exercise. Moreover, the fatigue from the conditioning activity may have still caused some residue fatigue and this finding has further support from the literature. Further investigations should continue to explore the differences in unilateral *vs.* bilateral exercises to see if the variables of loading and recovery could be optimized to achieve a PAP with a unilateral exercise. The benefits of this would stem from the enhanced use of unilateral exercises within the clinical setting and field settings because typically these exercises are easier to overload within these settings. Nonetheless, the results of the present investigation have shed new insights into the PAP phenomenon and uncovered new areas of inquiry for future investigations.

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