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# Changes in Dynamic Exercise Performance Following a Sequence of Preconditioning Isometric Muscle Actions

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**ABSTRACT**

Complex training is the method of coupling heavy and light loads into an organized sequence with the aim of facilitating postactivation potentiation. Anecdotal evidence has supported the use of complex training sequences, but scientific studies investigating the effects of sequencing isometric loads with dynamic muscle actions have been limited. The purpose of this study was to examine the effects of a preconditioning sequence of maximal isometric knee extensions on performance standards in selected dynamic whole-body exercise. Fourteen track and field athletes (23 ± 5.7 years; 71.53 ± 6.93 kg; 172.6 ± 5.8 cm) were randomly assessed in selected whole-body exercises (drop and countermovement jumps, 5-second cycle sprint, knee extension) following a sequence of maximal voluntary isometric contractions (MVC; 3 repetitions of 3 seconds or 3 repetitions of 5 seconds) or in the absence of prior loading (control). Electromyographic (EMG) assessments of muscle activity were also made during the knee extension assessment. Significant ($p \leq 0.05$) increases in jump height (5.03%), maximal force (4.94%), and acceleration impulse (9.49%) were observed in the drop jump following 3 repetitions of 3-second MVC only. Knee extension maximal torque was also significantly increased (6.12%) following the 3-second MVC. No significant changes in countermovement jump or cycle sprint measures were observed for any of the experimental conditions. Though adaptations were found, changes in EMG activity were not significantly different for any of the experimental conditions. These data indicate that performing a sequence of repeated maximal isometric knee extensions (3 repetitions of 3 seconds) prior to selected dynamic exercise (≤0.25 seconds) may have favorable effects on performance beyond standards achieved without prior heavy loading.

***Key Words:*** neuromuscular, force, contraction, complex training, potentiation

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## Introduction

The performance characteristics of skeletal muscle are transient in nature and can be affected by contractile history (17). Following heavy loading, subsequent muscle actions can be temporarily improved under the influence of increased excitability of the central nervous system (CNS) (6). This increased neural excitation is the result of an acute physiological adjustment (i.e., persistent change of up to 8–10 minutes) that has been referred to as postactivation potentiation (PAP) (11, 12, 17). PAP is recognized as an improvement in muscle-twitch force following ''conditioning'' contractile activity (e.g., maximal voluntary contraction) (17). The underlying premise surrounding PAP is that prior heavy loadings induce a high degree of neural stimulation that results in greater motor unit recruitment and higher-frequency rate coding for several minutes afterward (16). The effect of PAP is observed as a positive bias for subsequent muscle actions, with the magnitude and the decay characteristics of the bias related to the intensity and duration of the conditioning precontraction (19). Because of the prolonged nature of PAP, this phenomenon offers a theoretical strategy for optimizing force and power production beyond performance standards achieved without prior loading.

Coupling heavy and light loads into an organized sequence can facilitate the heightened neural activity associated with PAP, and this has been referred to by some as ''complex training'' (4, 6, 7). Complex training protocols offer a novel exercise sequence based on the principle that exercise for the development of reactive ability can be fulfilled in a background of heightened CNS excitability, brought about by preliminary fulfillment of exercise requiring great power (24). For example, it is not uncommon in complex training methods to couple maximal contractions and plyometric exercises together in sequence (e.g., squat followed by depth jumps) (4, 6). In this manner, movement patterns that follow heavy loading are believed to optimize the training effect through enhanced involvement of the nervous system (4). This has been demonstrated by Gullich and Schmidtbleicher (9), who found significant improvements in the rate of force development and jump height during repeated countermovement jumps following heavy loading in the form of repeated maximal voluntary contractions (MVC). Hamada et al. (11) have also identified potential benefits of complex training sequences, with enhanced twitch potentiation of the elbow extensors and ankle plantarflexor muscles of trained endurance athletes following MVC.

Increasing evidence indicates that the extent of neural excitation achieved following heavy loading is greatest within fast, type II muscle fibers (11, 12, 17). This is largely because fast-twitch fibers undergo greater phosphorylation of myosin regulatory light chains in response to conditioning activity (21). PAP consequently holds most benefit for athletes participating in events that require sudden brief efforts of activity (throwing, jumping, hitting). Although previous studies have indicated the beneficial properties of prior heavy loading on both neural excitation (11, 13, 20) and twitch characteristics (11, 23), the efficacy of a sequence effect that is beneficial to athletes participating in explosive sporting activity warrants further investigation. Prior research has provided evidence for the existence of PAP (11, 12, 17), but few studies have suggested suitable methods for use within the field to recruit the improved neural state associated with PAP and consequently to benefit appropriate athletic performance.

Complex training protocols may offer athletes a simple method of inducing the enhanced neural activity associated with PAP. Few studies, however, have examined the extent to which simple static, or isometric, muscle actions can be used to facilitate dynamic whole-body exercise. Basic isometric efforts can be performed with ease prior to competition or training without the need for special training equipment. Such exercises are therefore appealing because of the simple manner in which they can be included in an athlete's warm-up or exercise preparation. It was the aim of this study to investigate the feasibility of using repeated isometric muscle actions as a means of developing a heightened neural state (i.e., PAP) beneficial to the force-velocity characteristics of explosive whole-body exercise. It was proposed that if isometrically induced PAP were seen to promote dynamic whole-body exercise, maximal performances beyond those attained without prior loading could be achieved under conditions of improved neural excitation.

## Methods

### *Experimental Approach to the Problem*

The study was a randomized, balanced, test-retest design in which subjects were assessed in a series of exercise measures under 2 experimental conditions: (a) without prior loading, and (b) following repeated isometric MVC. The design allowed for comparison (i.e., test-retest) of the effects of contractile history between ''normal'' exercise standards and the standards achieved following preconditioning contractions (i.e., a complex training sequence). The battery of dynamic exercises assessed included drop jumps, countermovement jumps, a 5-second cycle sprint, and an isokinetic knee extension. Isokinetic exercise modalities were included in the study to remove the effects of contractile speed and to examine how levels of maximal force alone can be modulated by complex training sequences. Measures of muscular activity were also made using electromyographic (EMG) procedures. The randomized approach served to minimize the potential effects of learning. Subjects were required to report to the laboratory on 10 separate occasions. During any one visit to the laboratory subjects were assessed in no more than 2 of the dynamic exercise measures (e.g., drop jumps without prior loading and knee extension following repeated MVC), each separated by a minimum of 30 minutes. Thirty minutes has been shown to be an adequate duration for the removal of the residual effects of PAP (1). Individual testing sessions were separated by at least 72 hours, and no assessments were performed on competition or heavy training days. Test-retest reliability coefficients ($R$) for the day-to-day reproducibility of each of the performance measures were recorded at $R \geq 0.90$.

### *Subjects*

Fourteen healthy track and field athletes (men: $n = 10$; women: $n = 4$) volunteered to participate in the study (age: 23 ± 5.7 years; weight: 71.53 ± 6.93 kg; height: 172.6 ± 5.8 cm). All subjects were informed of the purpose and possible risks of the investigation prior to signing an informed consent document approved by the Institutional Review Board of Leeds Metropolitan University. Subjects completed a health-screening questionnaire, and each was cleared of any medical disorders that might confound or limit their ability to participate fully in the investigation. Subjects were actively competing at the time of testing, and the sample included 4 national-level and 2 international-level track and field athletes. All subjects had a history of resistance exercise >2 years.

### *Experimental Protocol*

Subjects reported to the laboratory having abstained from exercise and caffeine for 24 hours prior to testing. The time of testing was constant throughout the study. Measures of body mass were made on each visit to the laboratory in order to monitor subject weight. Prior to testing, subjects carried out a standardized warm-up consisting of 5 minutes submaximal cycling (60 W at 0.5-kg load) followed by light stretching and submaximal familiarization trials of the assessment exercises. Following the warm-up, subjects were seated for 15 minutes to allow for the residual effects of lingering neural potentiation to be removed.

Each subject was randomly assigned the order in which to perform the exercise assessment and, where required, the preloading (i.e., repeated isometric MVC). When measures of exercise performance were made under the experimental condition of no preload (i.e., control), assessments were carried out in a simple test-retest fashion. In the case of complex training sequences, assessments were again made in a test-retest fashion, but repeated isometric MVCs were incorporated into the activity sequence. In order to randomize assignment and to minimize sequence repetition, preloading was performed either prior to the initial exercise assessment or between the initial and posttest. In all experimental conditions comparisons were made between the rested or ''normal'' exercise performance and the exercise performance following preloading (i.e., complex training sequence).

### *Preconditioning Contractions*

Where required, isometric MVC of the knee extensors served as the preconditioning load. In all cases, voluntary contractions were carried out using the Cybex Norm isokinetic dynamometer (Cybex International Inc., Ronkonkoma, NY). Subjects were seated in an upright position and secured around the chest and thigh. The legs were positioned at 90° of knee flexion and secured to the dynamometer's lever arm according to the manufacturer's guidelines, just proximal to the medial malleolus. During the voluntary muscle actions subjects were instructed to perform maximal-effort leg extensions against the level arm of the dynamometer. Visual feedback was provided such that predetermined maximal force requirements were displayed on a screen. A horizontal line at the required force level was used to identify appropriate force applications.

The protocol for preconditioning consisted of 3 sets of single maximal-effort knee extensions. To quantify how the nature of the preload sequence affected exercise performance, 2 repetition durations were investigated. On separate occasions, each exercise was assessed following 3 sets of either 3- or 5-second contractions. The rationale for the selection of the exercise volumes used was based on the findings of pilot data and related studies within the literature (9, 11). Each maximal contraction was separated by a 3-minute interval. Following precontraction conditioning, post-MVC performance assessments were made immediately following the completion of the last repetition. Where exercise assessments were made under normal conditions without any prior loading, test-retest procedures were separated by 10 minutes, with the subjects remaining seated throughout.

### *Experimental Measures*

*Vertical Jumps.* Assessments of vertical jump were made using 2 exercise protocols: (a) countermovement jumps, and (b) drop jumps. On separate occasions a series of 5 countermovement or 5 drop jumps were performed at 30-second intervals. During both countermovement-jump and drop-jump protocols, subjects were instructed to maintain their hands in a position on the iliac crest in an attempt to remove extraneous variance resulting from arm swing.

Countermovement jumps were initiated from a standing position. Upon command, subjects squatted to what they considered an optimal depth (approximately one-third of a full squat), then immediately jumped vertically for maximal height. Drop-jump procedures began with the subjects standing on a 30-cm platform. Subjects were then requested to transfer from the platform, make a 2-footed landing, and jump vertically for maximum height. For each drop jump, subjects were instructed to minimize ground contact times.

Ground reaction forces were measured (1,000 Hz) using a Biovec 1100 force plate and accompanying Biosoft software (Advanced Medical Technologies Inc., Watertown, MA). Flight times were recorded using Ergojump contact mats (Junghans GMBH, Schramberg, Germany) positioned over the force plate. Jump height was determined for each of the 5 jumps using an acknowledged flight-time calculation (3). In all cases, the mean maximal jump height of the 5 jumps was used for data analysis.

*Five-Second Cycle Sprint.* The bicycle sprint allowed the investigators to monitor prolonged changes in force characteristics. The 5-second cycle sprint was carried out using a Monark 814E Ergomedic friction-loaded cycle ergometer (Monark-Crescent AB, Varberg, Sweden). Throughout the assessment subjects wore toe clips and were restrained in a seated position. For 20 seconds prior to data collection, subjects maintained an unloaded steady state cadence of 60 revolutions$\cdot$min$^{-1}$. Upon commencement of the test, a load relative to 0.075 kg$\cdot$kg$^{-1}$ was applied to the flywheel (2). It has been noted that larger power values can be obtained with loadings greater than that chosen (8), but the focus of this measure was for comparative purposes only, and thus the intensity of the loading was considered suitable. Subjects were instructed to cycle maximally for 5 seconds, and each was given verbal encouragement throughout. Measures of peak power output and time to peak power were collected using a flywheel-mounted optical sensor and recorded via computer interface using SMI Power software (Sports Medicine Industries Inc., St. Cloud, MN).

*Isokinetic Knee Extensions.* Performance assessments of isokinetic knee extensions were made using the Cybex Norm isokinetic dynamometer system previously discussed. Each subject was restrained in an upright-seated position, with the dominant leg secured to the lever arm according to manufacturer's guidelines. A single-repetition knee extension was performed through the subject's full range of motion, from maximum flexion to full extension and then immediately returning to full flexion. Use of the Cybex system allowed for regulation of the joint angular velocity at $250°\cdot s^{-1}$. Data were sampled at a frequency of 1,000 Hz and stored using Cybex software.

### *Electromyographic Assessment*

EMG data from the vastus medialis of the assessment limb were collected during the knee extension exercise. Prior to electrode application the skin was shaved, abraded, and cleansed with alcohol. Disposable bipolar Ag-Ag/Cl self-adhesive electrodes with a monopolar surface electrode configuration were applied to the surface of the skin, aligned with the anticipated muscle fiber orientation. The electrodes were positioned on a longitudinal axis 5 cm proximal to the patella, prior to its insertion to the tibial tuberosity through the patellar ligament. Interelectrode distance was 30 mm. A further reference electrode was placed over the proximal tibial bone. Each of the electrodes remained undisturbed throughout all stages of the test-retest procedures. EMG data were collected at 1,000 Hz using the Biopac MP100A recording and acquisition system (Biopac, Santa Barbara, CA), employing the accompanying software program for data reduction. All data were filtered using a 6-Hz first-order Butterworth high-pass filter. Saved EMG data were full-wave rectified and integrated for analysis purposes ($EMG_{int}$).

### *Statistical Analyses*

A 3 × 2 [group (3 seconds, 5 seconds, no treatment) × test (pretest, posttest)] factorial, 2-way analysis of variance procedure was used to test for statistically significant differences in exercise performance. In the event of a statistically significant *F*-ratio, the Tukey post-hoc test was employed to examine where group differences lie. Alpha levels for statistical significance were set at $p \leq 0.05$ throughout the analysis. Analyses were conducted using the SPSS version 10.0 statistical software program (SPSS Inc., Chicago, IL).

## Results

Following the 3-second contraction sequence, drop-jump flight height increased significantly ($p \leq 0.05$) by 5.03%. Mean flight height also increased following the 5-second contraction sequence, although these changes were not shown to be significant. No significant changes were found in the absence of preconditioning loading (i.e., control conditions) (Figure 1). Analysis of ground reaction forces indicated that all measures of flight height were achieved without significant differences in ground contact times. For all experimental conditions this period was consistently achieved in ≤0.235 seconds.

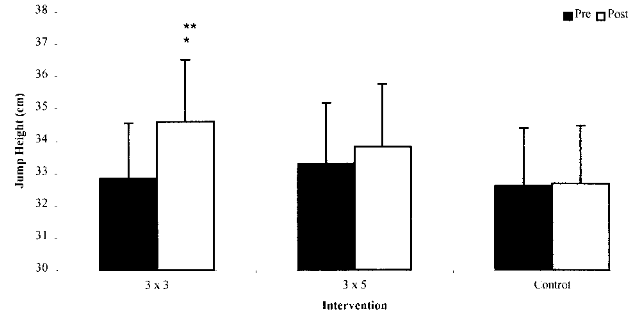


**Figure 1.** Changes in drop-jump flight height following repeated isometric contractions of the knee extensors. Values are means ± *SEM* and represent pre- and posttest assessments under each of the experimental conditions (3 × 3 seconds, 3 × 5 seconds, control). $^{*}p < 0.05$ from pretest; $^{**}p < 0.05$, significantly different from other sequence protocols.

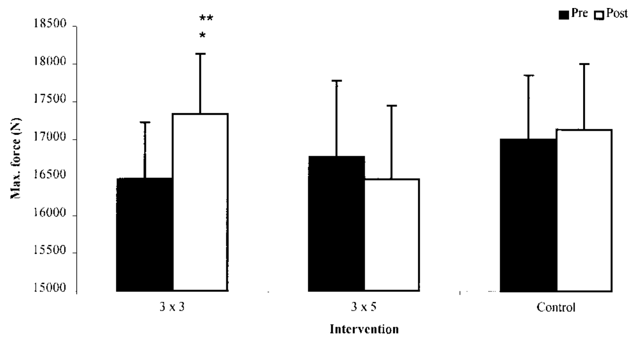


**Figure 2.** Changes in drop-jump maximal force following repeated voluntary isometric contractions of the knee extensors. Values are means ± *SEM* and represent pre- and posttest assessments under each of the experimental conditions (3 × 3 seconds, 3 × 5 seconds, control). $^{*}p <$ 0.05 from pretest; $^{**}p < 0.05$, significantly different from other sequence protocols.

Ground reaction force data indicated that the peak force ($F_{peak}$) achieved during the drop-jump protocol was significantly increased by 856.83 N (4.94%) following the 3-second contractions (Figure 2). Following 5-second contractions a 290.57 N (–1.73%) reduction in $F_{peak}$ was found, but this change was not shown to be significant. No significant difference in $F_{peak}$ was observed between pre- and posttest assessments under the control condition. At the point of $F_{peak}$ the ratio between force and velocity was quantified as the acceleration impulse ($N\cdot s^{-1}$). The acceleration impulse significantly increased by 148.57 $N\cdot s^{-1}$ (9.49%) after subjects performed the 3-second MVCs (Figure 3). A 77.1 $N\cdot s^{-1}$ (−5.03%) decrement in the force impulse

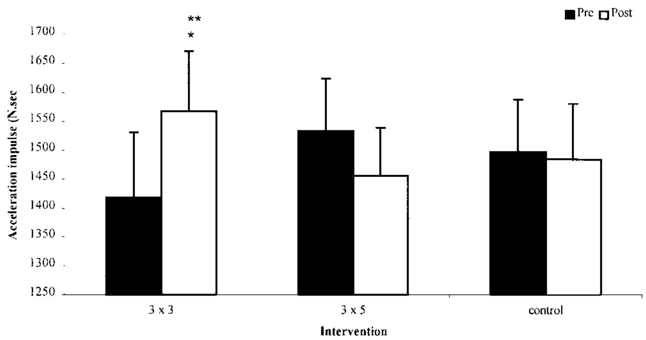


**Figure 3.** Changes in drop-jump acceleration impulse following repeated voluntary isometric contractions of the knee extensors. Values are means ± *SEM* and represent pre- and posttest assessments under each of the experimental conditions (3 × 3 seconds, 3 × 5 seconds, control). *$p < 0.05$ from pretest; **$p < 0.05$, significantly different from other sequence protocols.

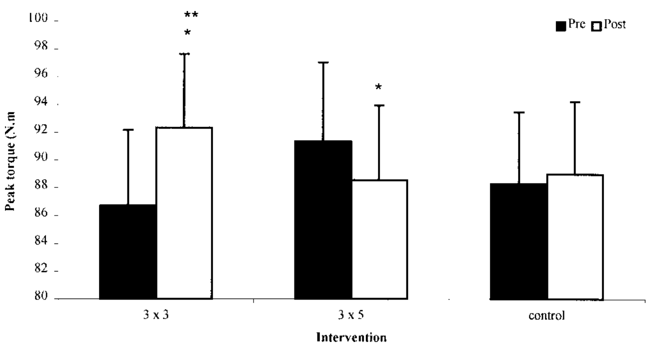


**Figure 4.** Changes in knee-extension peak torque following repeated voluntary isometric contractions of the knee extensors. Values are means ± *SEM* and represent pre- and posttest assessments under each of the experimental conditions (3 × 3 seconds, 3 × 5 seconds, control). *$p < 0.05$ from pretest; **$p < 0.05$, significantly different from other sequence protocols.

occurred following the set of 5-second contractions, but this decrease was again found to be nonsignificant. Force measures in the absence of any preloading were also not significantly different from each other.

Analysis of countermovement-jump data indicated no significant differences in mean jump height during any of the experimental conditions. Furthermore, ground reaction force data were also found to have no significant changes in force characteristics ($F_{peak}$, acceleration impulse) for each of the experimental procedures.

Peak torque ($T_{peak}$) achieved during the isokinetic knee extension significantly increased by 7.67 N·m (6.12%) following the 3-second isometric contractions (Figure 4). $T_{peak}$ was shown to significantly decrease following the set of 5-second contractions, with a reduction of 3.78 N·m (−3.05%) found in exercise performance consequent to a complex training sequence of this nature. No significant changes in the joint angle

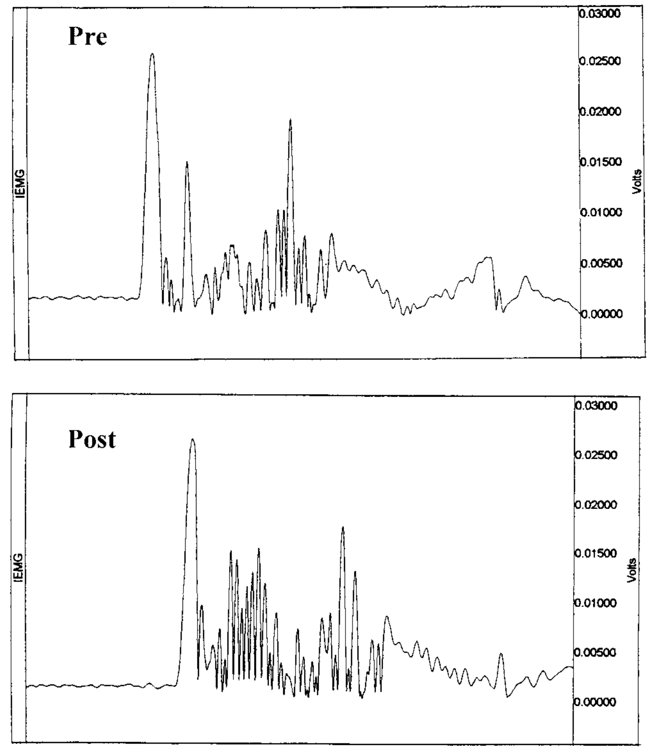


**Figure 5.** Typical electromyographic (EMG) data recorded during the isokinetic knee extension prior to (Pre) and immediately following (Post) 3 isometric MVC of 3 seconds. EMG data represent muscular activity during the concentric phase of the movement. Note that post-MVC activity indicates enhanced EMG activity in the form of increased amplitude and firing frequency during the contraction.

at which $T_{peak}$ was achieved were found for any of the exercise conditions.

Absolute peak power ($P_{peak}$) levels during the 5-second cycle sprint increased by 11.92 W (1.43%) following the 3-second contractions, decreased 5.79 W (0.71%) following the 5-second contractions, and increased 13.21 W (1.91%) without any preloading. None of these changes were found to be significant. Analysis of the time taken to achieve $P_{peak}$ also indicated that there were no significant changes within any of the experimental conditions.

### *EMG Responses*

No significant differences ($p > 0.05$) for $EMG_{int}$ of the vastus medialis were found for any of the experimental conditions during the knee extension. Characteristic adaptations in EMG amplitude were apparent following preconditioning loadings (3-second contractions increased 2%; 5-second contractions decreased 5.5%) (Figure 5). However, absence of change beyond the acceptance level for statistical significance ($p \geq 0.072$) did not allow for further analyses.

## Discussion

The primary findings of this investigation indicate that the use of isometric muscle actions within a complex training sequence may promote improved performance in selected dynamic whole-body exercises. Data show that improvements are sensitive to the nature, or structure, of the complex training sequence. Most notably, the total volume of the composite preconditioning load appears to play a significant role in determining the neuromuscular response. Furthermore, results indicate that complex training sequences are most beneficial to those exercises that rely upon high rates of force application (i.e., explosive power), with exercises that do not reflect such force characteristics showing no positive responses to complex training protocols.

Following a complex training sequence composed of 3 sets of 3-second isometric knee extensions, significant improvements in selected explosive dynamic muscle actions (drop jump, knee extension) were found. In comparison, preconditioning sequences consisting of 3 sets of 5-second contractions had no beneficial effect on the same exercises, and in some cases (e.g., countermovement jump), exercise standards were significantly reduced following the greater preload volumes. Total preconditioning contraction times therefore appear to modulate physiological responses. From the findings of this study, it is apparent that a total contraction volume of ≥15 seconds (i.e., 3 sets of 5-second MVC) induces a muscular fatigue that is sufficiently severe to eliminate the beneficial effects of PAP. In contrast, a smaller preconditioning volume (i.e., 9 seconds, or 3 sets of 3-second MVC) facilitates a heightened neural environment (i.e., PAP) that can coexist with fatigue and that is consequently reflected during ensuing muscular activity. These findings support those of Vandervoort and colleagues (23), who observed that the extent of potentiation was depressed if preceded by an MVC that exceeded 10 seconds. Using dynamic muscle actions, MVCs of 5 and 10 seconds have previously been found to be appropriate stimuli for the development of PAP (22, 23). Dynamic MVCs induce a neural potentiation that facilitates CNS pathways and promotes the sensory responses controlling short-duration muscle actions (22). Present data support the earlier findings using dynamic muscle actions and indicate that a composite of repeated isometric contractions (3 sets of 3-second MVC) can also serve as a stimulus for improved dynamic exercise performance.

The expression of PAP gives an athlete the potential to improve the performance of explosive dynamic muscle actions (9). Explosive muscle actions have been described by Haff et al. (10) as contractions with an activation period of ≤0.25 seconds, where initial and maximal rates of force development are the primary factors affecting performance. Following repeated 3-second knee extensions, improved exercise performance was observed in the drop-jump and knee-extension measures only. The mean duration of contractile activity during these exercises was found to occur in ≤0.235 seconds. In contrast, time-motion analysis of the countermovement jump and cycle sprint indicated a prolonged activity beyond 0.25 seconds. In light of these extended durations, the countermovement jump and cycle sprint do not adhere to the defining characteristics of explosive activity described by Haff et al. (10). It may not, therefore, be surprising that the effects of PAP were absent from these measures. Owing to the ability of a particular complex training sequence (i.e., 3 sets of 3-second MVC) to serve as a mediator of drop-jump and knee-extension performance, it is apparent that the nature of the exercise can play a profound role in modulating PAP expression. These findings support the work of Hamada et al. (11), who have also indicated that the effects of PAP are best observed during high-velocity muscle actions (i.e., <0.25 seconds), with prolonged contractions demonstrating a reduced capacity for augmentation.

Contractile speed is thought to be one of the major determinants of explosive muscle actions (5). However, previous studies of PAP have also indicated that an increase in the height of the dynamically realized force maximum may accompany changes in the force application rates (9). The significant changes in drop-jump flight height (5.03%) are considered to be the net result of significant improvements in both the $F_{peak}$ (4.94%) and the acceleration impulse (9.49%). Furthermore, with the angular velocity of the knee extension held constant, thus controlling for changes in rates of force application, the significant improvements in $T_{peak}$ (6.12%) following preconditioning contractions (3 sets of 3-second MVC) indicate that the magnitude of force can be improved by complex training sequences. These significant adaptations following a composite of isometric contractions in the form of a complex training sequence indicate that ''rate of contraction'' is not the only adaptation in muscle function that can be affected by suitable complex training protocols. Shea et al. (19) report that the positive improvements in $F_{peak}$ following a potentiating contraction are the direct result of increased firing rates, greater recruitment of the neuronal pool, and improved synchronization of motor patterns. Present data indicate that performing repeated isometric MVCs prior to explosive dynamic exercise can have beneficial effects not only on those exercises that require rapid rates of force development, but also on those that are facilitated through improvements in maximal force outputs.

Increased EMG activity of human motor units has been recorded following isometric muscle actions (9), and strength training studies have further demonstrated increased EMG activation of reflex potentiation after the performance of MVC (18). Though not significant, present data indicate that EMG responses showed a pattern of increased neural activity following 3 sets of 3-second isometric MVC. What is more, this increased neural activity appeared to differ from the EMG responses of 3 sets of 5-second contractions. Although it was not possible to make definitive judgments using present data, the increased amplitude following the 3-second contractions is most likely an indication that preconditioning contractions resulted in a greater number of activated motor units. It may be suggested that during future analyses of this nature, a collection frequency of greater than 1,000 Hz is required in order to quantify any significantly changed expressed in response to neural facilitation.

Complex training protocols that facilitate the ergogenic characteristics of PAP may benefit a wide range of athletic populations. Indeed, previous research has shown postactivation potentiation to be independent of personal characteristics (age, gender) and training status (9, 15). The neural excitation achieved following heavy loading is greatest within type II muscle fibers (11, 12, 17), and thus PAP holds most benefit for athletes participating in events that require sudden, brief efforts of activity. Previous research has, however, suggested that the extent of PAP adaptation is not sufficiently severe to warrant the use of such intensive neuromuscular conditioning prior to competitive performance (14). Within this population of trained athletes, the present data have indicated that even in highly conditioned individuals, valuable acute increases in exercise performance can still be observed when employing specific complex training protocols. It is suggested that the slight reduction observed in drop-jump contraction times and the improvements in knee extension $T_{peak}$ indicate that these power athletes still maintain sensitivity to the intensification rather than the prolongation of the active state. PAP can therefore be considered functionally important, not only in the development of maximum sustained force, but also in those situations where sudden, brief efforts are required (throwing, jumping, hitting) (23). By using the PAP effects of short-term isometric MVC, improved performances may be obtained by integrating complex training sequences into a functional warm-up program for training or competition.

## Practical Applications

Complex training sequences have the potential to promote the neural state associated with PAP, and they represent an exercise protocol that can be used to optimize the performance of selected explosive muscle actions. Fundamental to the expression of PAP is that both the nature of the exercise and the volume of the preconditioning stimulus serve to modulate the extent of adaptation observed. In highly trained athletes, significant improvements in exercise performance can be achieved for muscle actions that are fulfilled in 0.25 seconds or less (e.g., sprint starts, throwing, jumps). Using a composite of repeated isometric contractions, contractile sequence volumes of approximately 10 seconds in total appear to be more beneficial than larger volumes (e.g., 15 seconds), which most likely facilitate greater levels of muscular fatigue. Though the extent of performance adaptation using complex training is small, the potential benefits that such acute improvements in performance hold to a highly conditioned elite athlete should not be underestimated. Complex training protocols that adopt basic isometric muscle actions (e.g., partner assisted, pushing or pulling against immovable objects) are a practical means of inducing PAP without the need for heavy or bulky equipment, and they can therefore be performed without restriction in most environments (e.g., on the track, in the gym). The present study has made initial efforts to indicate that repeated maximal ''isometric'' contractions might offer a simple exercise sequence that induces a potentiated neuromuscular environment conducive to enhanced performance during explosive dynamic muscle actions. What is more, such augmented performances are observed beyond the exercise standards achieved without prior heavy loading.

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