

Research Paper



Acute Effects of Post-Activation Performance Enhancement-Based Warm-Up Protocols on Knee Joint Kinematics and Countermovement Jump Performance in Male Physical Education Students

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ABSTRACT

Objective This study investigated the acute effects of resistance-based and combined post-activation performance enhancement (PAPE) warm-up protocols on knee joint kinematics and countermovement jump (CMJ) performance in male physical education students.

Methods This quasi-experimental study used a repeated-measures crossover design. Twenty male physical education students (age: 21 ± 2.00 years; height: 176 ± 5 cm; body mass: 70 ± 5 kg; sport experience: 8 ± 2.2 years) were recruited by convenience sampling. Each participant completed three warm-up conditions in separate, non-consecutive sessions: general warm-up, resistance warm-up, and combined warm-up. The order of conditions was counterbalanced. After each protocol and a 2-min recovery period, participants performed the CMJ. Three-dimensional kinematic data were collected using a six-camera Motion Analysis Raptor-H system sampling at 200 Hz. Outcome variables included jump height, peak knee flexion before take-off and during landing, and peak knee angular velocity during eccentric and concentric phases. Data were analyzed using repeated-measures analysis of variance with Bonferroni-adjusted post hoc comparisons.

Results Both resistance and combined warm-up protocols significantly increased jump height, knee flexion, and knee angular velocity compared with the general warm-up condition ($p = 0.001$). Although the combined protocol produced higher numerical values for several outcomes, no statistically significant differences were observed between the two PAPE-based protocols ($p > 0.05$).

Conclusion PAPE-based warm-up protocols acutely improved CMJ performance and selected knee joint kinematic characteristics. These protocols may be useful as part of pre-activity preparation for explosive tasks when implemented with appropriate load selection and recovery time.

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1. Introduction

Lower-extremity explosive power is a key performance component in many sports and contributes directly to jumping, landing, acceleration, cutting, and other high-intensity actions. In team and individual sports, the capacity to generate force rapidly is closely related to successful performance. For this reason, sport scientists and strength and conditioning practitioners continue to seek acute and chronic strategies that enhance neuromuscular readiness and power output (1,2).

The countermovement jump (CMJ) is one of the most frequently used tests for evaluating explosive power and stretch-shortening cycle function. The test is simple to administer, has good practical reliability, and is closely linked to performance in tasks requiring rapid lower-extremity force production. During the CMJ, the athlete first flexes the lower-extremity joints during the eccentric phase and then immediately extends them to jump vertically. Effective CMJ performance therefore depends on inter-joint coordination, force-production capacity, and efficient use of elastic energy within the muscle-tendon unit (3,4).

From a biomechanical perspective, jump performance is not defined only by the final jump height. It reflects the coordinated interaction of lower-limb joint torque, rate of force development, force-application time, and joint motion patterns during the eccentric and concentric phases. Previous work has shown meaningful associations between jump height and hip and knee flexion-extension torques in young men, suggesting that the strength of the hip and knee joints may be a determining factor in successful jumping tasks. In more complex jumping skills, variables such as jump height, vertical velocity, flight time, and hip and knee angular velocity have also been treated as key biomechanical indicators. Examining both performance and kinematic outcomes may therefore provide a more complete understanding of how neuromuscular preparation strategies affect jumping performance (5,6).

The knee joint is one of the most functionally important joints in the lower limb and contributes substantially to load bearing, stability, balance, and movement execution. During the CMJ, the knee is involved in force absorption during landing, force transfer during the propulsive phase, and elastic energy storage during the eccentric phase. Changes in knee joint angles and angular velocities may influence jump performance, mechanical load distribution, and the risk of sport-related injuries. Reduced knee flexion during landing has been associated with greater shear loading and a higher risk of anterior cruciate ligament (ACL) injury (7-9). For this reason, the kinematic response of the knee joint to warm-up interventions deserves specific attention.

The importance of knee kinematics in jump-landing tasks becomes clearer when reduced knee flexion and increased knee valgus or abduction are considered as movement patterns that may shift landing mechanics toward higher risk. Studies of jumping and landing have shown that changes in knee flexion and valgus, particularly in the dominant limb, may indicate greater mechanical joint loading and a higher likelihood of ACL injury. Research on CMJ and jump-landing tasks also suggests that lower-limb kinematic variables--especially knee range of motion during the eccentric and concentric phases, peak flexion, and the instant of landing--are sensitive to training conditions, fatigue, and corrective interventions. Assessing the effects of PAPE-based warm-up protocols on knee flexion and angular velocity is therefore valuable not only for explaining jump-performance changes but also for evaluating movement quality and landing safety (10-12). One strategy that has received growing attention for improving explosive performance is post-activation performance enhancement (PAPE). Although the term post-activation potentiation (PAP) has traditionally been used, the term PAPE is now often preferred when describing improvements in voluntary sport performance after conditioning contractions. PAPE refers to an acute enhancement of subsequent muscular performance following a preceding voluntary contraction. Proposed mechanisms include phosphorylation of myosin regulatory light chains, increased alpha-motor neuron excitability, greater motor-unit recruitment, and improved neuromuscular coordination (13-15).

Long-term training interventions are commonly used to improve jump performance, but acute preparatory strategies may also transiently increase lower-extremity power during warm-up. These short-term improvements are generally attributed to PAPE-related mechanisms and neuromuscular facilitation (16). Heavy resistance exercises, particularly squat-based conditioning activities, are frequently used to elicit PAPE responses and have been shown to improve vertical jump and explosive performance in some studies (17,18). Combined protocols that use free weights with elastic bands may provide an additional variable-resistance stimulus because external resistance increases through the range of motion as mechanical advantage improves (19).

Despite this rationale, findings regarding PAPE effects on jump performance and biomechanical variables remain inconsistent. Some studies have reported meaningful improvements in jump height and explosive power, whereas others have observed little or no change (20,21). Most previous work has focused on performance outcomes such as jump height or power, with less attention to knee joint kinematics after PAPE interventions. In addition, direct comparisons between traditional resistance warm-up and combined warm-up protocols using elastic bands are still limited, particularly in Iranian physical education students. From an applied perspective, understanding how different PAPE protocols affect knee joint kinematics may help coaches, strength and conditioning specialists, and biomechanists design warm-ups that enhance performance without compromising movement quality. If a warm-up strategy improves explosive performance while supporting safer landing mechanics, it may be useful before training sessions and competitions. The purpose of the present study was therefore to compare the acute effects of two PAPE-based warm-up protocols--a resistance warm-up and a combined warm-up using free weights plus elastic bands--on knee joint kinematics and CMJ performance in male physical education students. We hypothesized that both PAPE protocols would improve performance and kinematic outcomes compared with a general warm-up, and that the combined protocol would produce the greatest numerical response.

2. Methods

2.1. Participants

The present study used a quasi-experimental repeated-measures crossover design. The target population consisted of male physical education students at Shahid Bahonar University of Kerman. Twenty participants (age: 21 ± 2 years; height: 176 ± 5 cm; body mass: 70 ± 5 kg; sport experience: 8 ± 2.2 years) were recruited through convenience sampling. Sample size was estimated using G*Power based on effect sizes reported in comparable studies, with statistical power set at 80% and alpha at 0.05. Inclusion criteria were male sex, enrollment in physical education, at least three years of regular sport participation, no lower-extremity injury during the previous six months, no history of orthopedic surgery, and no heavy resistance training during the previous six months. Exclusion criteria were failure to complete all testing sessions or incorrect execution of the assigned protocols.

Before testing, all participants received a full explanation of the study procedures, testing conditions, potential risks, and experimental requirements. Written informed consent was obtained from each participant. All testing sessions were conducted between 9:00 a.m. and 2:00 p.m. to reduce the influence of diurnal variation.

2.2. Training Protocols

Each participant completed three warm-up conditions--general warm-up, resistance warm-up, and combined warm-up--in three separate, non-consecutive sessions. The order of conditions was counterbalanced to reduce learning and order effects (Table 1).

Following the protocol described by Rezaei Lori et al. (1), each session included 5 min of jogging, 3 min of dynamic stretching, and the assigned warm-up condition. After the specific warm-up protocol, participants rested for 2 min before performing the CMJ test.

One week before data collection, participants completed a one-repetition maximum (1RM) assessment for the squat exercise using a trial-and-error procedure across 4-6 attempts. This assessment was used to prescribe the loading intensity for the resistance and combined warm-up protocols.

2.2.1. General Warm-Up Protocol

Participants ran on a treadmill for 5 min at 8-9 km/h, followed by 3 min of dynamic stretching targeting the quadriceps, hamstrings, calf muscles, and lumbar region. Each stretch lasted approximately 4-6 s. Participants then performed five bodyweight squats (22).

2.2.2. Resistance Warm-Up Protocol

Participants performed one set of five squat repetitions at 85-90% of 1RM.

2.2.3. Combined Warm-Up Protocol

In the combined protocol, participants performed squats using both free weights and elastic bands (Fig. 1). The total exercise intensity was approximately 80% of 1RM, and participants completed three sets of three repetitions. No restriction was imposed on squat depth or knee joint angle; participants performed the movement using their natural squat pattern. Elastic bands were attached from the lower anchor point to the weight plates and from the upper end to the barbell, creating variable resistance across the movement range (14).

2.3. Elastic Band Calibration

Elastic bands were calibrated by suspending known loads from the distal end of the band and recording the corresponding change in length. A linear regression equation was then derived from the load-elongation relationship and used to estimate elastic resistance during the movement (18).

2.4. Kinematic Data Collection

Three-dimensional kinematic data were collected using a Motion Analysis Raptor-H system with six cameras sampling at 200 Hz. Marker trajectories were recorded in Cortex software (version 2.5) and filtered using a fourth-order low-pass Butterworth filter with a 12-Hz cutoff frequency. Camera placement was arranged so that each reflective marker was visible to at least two cameras throughout the movement (23). After calibration of the capture volume, participants performed the test while wearing minimal clothing to improve marker visibility. Four reflective markers were attached to anatomical landmarks on the dominant lower limb: the anterior superior iliac spine, greater trochanter, lateral femoral epicondyle, and lateral malleolus. Dominant-limb marker placement was selected on the basis of previous CMJ biomechanical studies and was used to simplify processing and reduce tracking error (23,24). For CMJ execution, participants stood upright with their hands placed on the iliac crests to remove the contribution of the upper limbs. They then rapidly flexed the knees to initiate the eccentric phase and immediately performed a maximal vertical jump by extending the lower-extremity joints (25). Each participant completed three trials, and the best trial was selected for analysis. Jump height was calculated from the vertical displacement of the right anterior superior iliac spine marker. The difference between the initial vertical position of this marker and its highest vertical position during the jump was used as jump height (16). The dependent variables were jump height, peak knee flexion before toe-off, peak knee flexion during landing, peak knee angular velocity during the eccentric phase before take-off, peak knee angular velocity during the concentric phase, and peak knee angular velocity during landing. The eccentric phase was defined as the interval from the initiation of knee flexion to the instant of movement reversal. The concentric phase was defined as the interval from the initiation of knee extension to toe-off.

Table 1. Counterbalanced order of warm-up conditions across subgroups

Day	First	Second	Third
Subgroup	Combined	Resistance warm-up	General warm-up
1	General warm-up	Combined warm-up	Resistance warm-up
2	General warm-up	Resistance warm-up	Combined warm-up
3	Resistance warm-up	General warm-up	Combined warm-up



Fig. 1. Combined warm-up protocol using free weights and elastic bands.

2.5. Statistical Analysis

Data normality was assessed with the Shapiro-Wilk test. A one-way repeated-measures analysis of variance was used to compare the three warm-up conditions. When a significant main effect was observed, Bonferroni post hoc tests were applied. The significance level was set at $p \leq 0.05$. All analyses were conducted in SPSS version 22.

3. Results

As shown in Table 2, repeated-measures ANOVA indicated significant differences among the three warm-up conditions for jump height. Bonferroni post hoc comparisons showed that jump height increased after the resistance warm-up (29.7 ± 1.1 cm) and combined warm-up (32.6 ± 1.5 cm) compared with the general warm-up (27.6 ± 0.2 cm) ($p = 0.001$). The difference between the resistance and combined protocols was not statistically significant ($p = 0.079$), although the combined condition produced the highest numerical value. Peak knee flexion before take-off also increased after the resistance warm-up (36.7 ± 1.9 degrees) and combined warm-up (44.5 ± 2.1 degrees) compared with the general warm-up (32.4 ± 1.8 degrees) ($p = 0.001$). The combined protocol produced a larger mean knee flexion angle than the resistance protocol, but the difference was not statistically significant ($p = 0.084$). Peak knee flexion during landing increased after the resistance warm-up (39.8 ± 1.7 degrees) and combined warm-up (48.7 ± 1.9 degrees) compared with the general warm-up (36.1 ± 1.5 degrees) ($p = 0.001$). Again, the difference between the two PAPE protocols did not reach statistical significance ($p = 0.100$). Overall, Table 2 indicates that PAPE-based warm-ups increased jump height and knee flexion before take-off and during landing. These changes may reflect more effective use of the stretch-shortening cycle and greater neuromuscular readiness before explosive activity.

Table 3 shows that peak knee angular velocity during the eccentric phase before take-off increased after the resistance warm-up (289.0 ± 15.8 deg/s) and combined warm-up (299.4 ± 19.1 deg/s) compared with the general warm-up (239.5 ± 9.8 deg/s) ($p = 0.001$). The resistance and combined protocols did not differ significantly ($p = 1.000$).

Table 2. Mean \pm standard deviation and pairwise comparisons of jump height and knee flexion variables across warm-up conditions

Variable	Comparison of warm-ups	Mean \pm SD	p-value
Jump height (cm)	General warm-up vs. Resistance warm-up	27.6 \pm 0.2 vs. 29.7 \pm 1.1	*0.001
	General warm-up vs. Combined warm-up	27.6 \pm 0.2 vs. 32.6 \pm 1.5	*0.001
	Resistance warm-up vs. Combined warm-up	29.7 \pm 1.1 vs. 32.6 \pm 1.5	0.079
Maximum knee flexion before jump (deg)	General warm-up vs. Resistance warm-up	32.4 \pm 1.8 vs. 36.7 \pm 1.9	*0.001
	General warm-up vs. Combined warm-up	32.4 \pm 1.8 vs. 44.5 \pm 2.1	*0.001
Maximum knee flexion during landing (deg)	Resistance warm-up vs. Combined warm-up	36.7 \pm 1.9 vs. 44.5 \pm 2.1	0.084
	General warm-up vs. Resistance warm-up	36.1 \pm 1.5 vs. 39.8 \pm 1.7	*0.001
	General warm-up vs. Combined warm-up	36.1 \pm 1.5 vs. 48.7 \pm 1.9	*0.001
	Resistance warm-up vs. Combined warm-up	39.8 \pm 1.7 vs. 48.7 \pm 1.9	0.100

*Indicates a significant difference.

Table 3. Mean \pm standard deviation and pairwise comparisons of peak knee angular velocity variables across warm-up conditions

Variable	Comparison of warm-ups	Mean \pm SD	p-value
Maximum angular velocity in eccentric phase before jump (deg/s)	General warm-up vs. Resistance warm-up	239.5 \pm 9.8 vs. 289.0 \pm 15.8	*0.001
	General warm-up vs. Combined warm-up	239.5 \pm 9.8 vs. 299.4 \pm 19.1	*0.001
	Resistance warm-up vs. Combined warm-up	289.0 \pm 15.8 vs. 299.4 \pm 19.1	1.000
Maximum angular velocity in concentric phase before jump (deg/s)	General warm-up vs. Resistance warm-up	253.7 \pm 10.3 vs. 320.9 \pm 16.4	*0.001
	General warm-up vs. Combined warm-up	253.7 \pm 10.3 vs. 329.3 \pm 19.5	*0.001
Maximum angular velocity in eccentric phase during landing (deg/s)	Resistance warm-up vs. Combined warm-up	320.9 \pm 16.4 vs. 329.3 \pm 19.5	0.060
	General warm-up vs. Resistance warm-up	237.2 \pm 11.9 vs. 307.0 \pm 15.4	*0.001
	General warm-up vs. Combined warm-up	237.2 \pm 11.9 vs. 320.0 \pm 18.4	*0.001
	Resistance warm-up vs. Combined warm-up	307.0 \pm 15.4 vs. 320.0 \pm 18.4	0.240

*Indicates a significant difference.

Peak knee angular velocity during the concentric phase before take-off also increased after both PAPE protocols. Mean angular velocity increased from 253.7 ± 10.3 deg/s in the general warm-up condition to 320.9 ± 16.4 deg/s after the resistance protocol and 329.3 ± 19.5 deg/s after the combined protocol ($p = 0.001$). The difference between the two PAPE conditions was not significant ($p = 0.060$). Peak knee angular velocity during the eccentric phase of landing increased after the resistance warm-up (307.0 ± 15.4 deg/s) and combined warm-up (320.0 ± 18.4 deg/s) compared with the general warm-up (237.2 ± 11.9 deg/s) ($p = 0.001$). The two PAPE protocols did not differ significantly ($p = 0.240$). Collectively, [Table 3](#) indicates that PAPE-based warm-ups increased knee angular velocity during different phases of the CMJ. The higher angular velocity may reflect an improved rate of force development and greater neuromuscular efficiency during explosive movement.

4. Discussion

The purpose of this study was to examine the acute effects of two PAPE-based warm-up protocols on knee joint kinematics and CMJ performance. Both the resistance and combined protocols significantly improved jump height and knee kinematic variables compared with the general warm-up condition. No statistically significant difference was observed between the two PAPE protocols. These findings suggest that high-intensity resistance activity before an explosive task can produce a short-term neuromuscular response that improves jump performance. The results are consistent with Wilson et al. (26), Gourgoulis et al. (8), and Tillin and Bishop (27), who reported that heavy resistance conditioning activities can acutely enhance explosive performance.

The improvement in jump height after the PAPE protocols may be explained by increased neuromuscular excitability and greater force-production capacity. PAPE has been linked to phosphorylation of myosin regulatory light chains, increased sensitivity of the actin-myosin complex to calcium ions, and a greater number of active cross-bridges (19,20). Increased motor-unit recruitment and higher motor-neuron discharge rates may also contribute to better explosive performance (21). These mechanisms are particularly relevant for movements such as the CMJ, which depend heavily on the stretch-shortening cycle.

The increase in jump height can also be interpreted through the role of the hip and knee joints in torque generation and force transfer along the lower-limb kinetic chain. In young men, jump height has been associated with hip and knee flexion-extension torques, indicating that improved neuromuscular readiness after PAPE protocols may enhance torque production in key lower-limb joints and allow more effective use of the eccentric phase. Findings from biomechanical analyses of more complex jumping skills also identify jump height, vertical velocity, flight time, and hip and knee angular velocity as important performance-related variables. The simultaneous increase in jump height and knee angular velocity in the present study therefore suggests that the PAPE protocols did not merely improve the final jump outcome, but may also have enhanced the mechanical quality of movement execution (5,6).

The increase in peak knee flexion before take-off has important biomechanical implications. Greater knee flexion before take-off may lengthen the time available for force application and improve the use of elastic energy stored during the eccentric phase. Previous biomechanical studies indicate that greater preparatory knee flexion can increase the contribution of the knee and hip extensors and enhance stretch-shortening cycle efficiency (22,23). Greater knee flexion during landing may also improve shock absorption and reduce knee joint loading, thereby supporting safer landing mechanics (24). The observed changes in knee flexion therefore appear to reflect a more favorable neuromuscular control strategy after the PAPE interventions.

The increase in knee flexion during landing is also relevant from a movement-safety perspective. Reduced knee flexion combined with greater knee valgus or abduction during jump-landing tasks can shift landing toward a higher-risk mechanical pattern and may increase ACL loading. Similar changes have been reported in the dominant limb after intensive training periods and during fatigued or later phases of sport activity. Corrective exercise and feedback-based interventions may increase lower-limb range of motion across the eccentric, concentric, peak-flexion, and landing phases while reducing knee valgus. On this basis, the greater knee flexion observed after the PAPE protocols in the present study may be interpreted not only as a performance-related change, but also as a softer landing strategy that supports force absorption and improves neuromuscular control of the lower limb (10-12).

Knee angular velocity during the eccentric and concentric phases also increased after the PAPE protocols. This response may indicate a higher rate of force development and improved coordination between agonist and antagonist muscle groups. In explosive tasks such as the CMJ, rapid force production is often more important than maximal force capacity alone. Consequently, higher knee angular velocity may contribute meaningfully to improved jump performance (28). The present findings are consistent with Shi et al. (29), Chen et al. (30), Beato et al. (31), and Arabatzi et al. (32), who reported improvements in explosive-force characteristics and kinematic variables after PAPE interventions.

Although the combined protocol produced higher numerical values than the resistance protocol, the differences were not statistically significant. One explanation is that the mechanical intensity of both protocols was sufficient to elicit a PAPE response, whereas the additional elastic-band stimulus was not large enough to produce a statistically superior effect. This finding is partly consistent with studies of variable resistance showing that elastic bands do not always provide additional improvements in explosive performance beyond traditional resistance exercise (33). In contrast, Sanchez-Sanchez et al. (34) and Marin et al. (35) reported positive effects of elastic-band resistance on vertical jump performance. Differences in load intensity, recovery duration, training status, or movement execution may explain the inconsistency. From a mechanical standpoint, elastic bands may enhance explosive performance by increasing resistance through the range of motion. As resistance rises in the terminal phase of the movement, neuromuscular stimulation and recruitment of fast-twitch motor units may increase, potentially improving the rate of force development and power output. The present findings suggest, however, that this additional stimulus did not produce a statistically superior response compared with resistance warm-up alone.

Only the dominant lower limb was analyzed in this study. Although unilateral analysis limits generalization to bilateral movement patterns, it is commonly used in CMJ biomechanical studies to reduce processing complexity and marker-tracking error (36,37). Future studies should include bilateral kinematic models, electromyography, and ground reaction force data to provide a more complete explanation of the neuromuscular mechanisms underlying PAPE responses.

Several limitations should be acknowledged. First, the sample was limited to male physical education students, which restricts generalization to female participants, elite athletes, and other sport populations. Second, electromyographic activity and ground reaction forces were not recorded. Third, only acute responses were examined; long-term adaptations to repeated PAPE exposure were not assessed. Finally, complete control of neuromuscular fatigue between testing sessions was not possible.

Despite these limitations, the findings have practical value for coaches, strength and conditioning specialists, and athletes. PAPE-based warm-up strategies appear capable of increasing neuromuscular readiness and improving CMJ performance. From an applied standpoint, either a traditional resistance warm-up or a combined warm-up may be used before explosive tasks depending on available equipment, athlete familiarity, and training context.

5. Conclusion

This study showed that PAPE-based warm-up protocols acutely improved countermovement jump performance and selected knee joint kinematic variables. Both resistance and combined warm-up protocols produced significant positive effects compared with the general warm-up condition, but the combined protocol was not statistically superior to resistance warm-up alone. These findings support the use of PAPE-based strategies as part of warm-up routines before explosive athletic activity.

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Ethical Considerations

Compliance with ethical guidelines

All procedures involving human participants were conducted in accordance with ethical standards for human-subject research. Written informed consent was obtained from all participants before data collection.

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Authors' contributions

Conceptualization, methodology, supervision, review, and editing: all authors. Original draft preparation and reference management: Ahmad Shokrollahi and Ali Amiri Khorasani.

Conflicts of interest

The authors declare that they have no conflict of interest associated with this study.

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