TITLE

Variable, but not free-weight, resistance back squat exercise potentiates jump performance following a comprehensive task-specific warm-up

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RUNNING HEAD

Elastic band use improves jump performance

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ABSTRACT

Studies examining acute, high-speed movement performance enhancement following intense muscular contractions (frequently called 'post-activation potentiation'; PAP) often impose a limited warm-up, compromizing external validity. In the present study the effects on countermovement vertical jump (CMJ) performance of back squat exercises performed with or without elastic bands during warm-up were compared. After familiarization, fifteen active men visited the laboratory on two occasions under randomized, counterbalanced experimental squat warm-up conditions: (1) free-weight resistance (FWR) and (2) variable resistance (VR). After completing a comprehensive task-specific warm-up, three maximal CMJs were performed followed by three back squat repetitions completed at 85% of 1-RM using either FWR or VR. Three CMJs were then performed 30 s, 4 min, 8 min and 12 min later. During CMJ trials, hip, knee and ankle joint kinematics, ground reaction force data and vastus medialis, vastus lateralis and gluteus maximus electromyograms (EMG) were recorded simultaneously using 3D motion analysis, force platform, and EMG techniques, respectively. No change in any variable occurred after FWR ($p>0.05$). Significant increases ($p<0.05$) were detected at all time points following VR in CMJ height (5.3-6.5%), peak power (4.4-5.9%), rate of force development (12.9-19.1%), peak concentric knee angular velocity (3.1-4.1%) and mean concentric vastus lateralis EMG activity (27.5-33.4%). The lack of effect of the free-weight conditioning contractions suggests that the comprehensive task-specific warm-up routine mitigated any further performance augmentation. However, the improved CMJ performance following the use of elastic bands is indicative that specific alterations in force-time properties of warm-up exercises may further improve performance.

Keywords: elastic bands, PAP, conditioning activity, explosive strength, kinetics, kinematics

INTRODUCTION

Pre-exercise (i.e. warm-up) routines are typically designed to precondition the neuromuscular system to enhance performance and reduce injury risk during subsequent high-intensity physical activities.[1-3] Performing maximal or near-maximal muscular contractions during a warm-up routine are important as they can induce short-term increases in force production and physical performance[4] through a number of mechanisms including, but not limited to, increases in muscle temperature,[5] reductions in muscle thixotropy or viscosity,[3] increases in myofilament calcium sensitivity,[6] an increased neural drive (leading to higher-frequency motor unit discharge) and optimization of motor control strategies.[7] Such changes lead to an increased mechanical power output (i.e. above previous maximal voluntary capacity), a state often referred to as post-activation potentiation (PAP) but which may not be synonymous with 'classic' PAP, which refers to an increase in muscular force production during an electrically elicited (twitch) contraction.[8] Regardless of the mechanism, short-term improvements in performance (i.e. post-activation performance enhancements [PAPE])[9] are commonly reported following intense muscular contractions that have important implications for the design of warm-up strategies.

The acute augmentation of physical performance has been explored using different warm-up strategies including light muscle stretching, cycling, running and sub-maximal repetitions of the primary task[10] or no warm-up at all.[8] Consequently, a "comprehensive task-specific" warm-up (including progressively intense task-specific conditioning activities) is often not provided prior to the specific activity being tested. Although warm-up strategies adopted to potentiate muscular force production have been shown to enhance athletic performance following a conditioning activity, it is unclear whether the enhancement of athletic performance observed is a consequence of acute neuromuscular alteration relating to the conditioning activity, or whether it simply reflects a standard warm-up itself.[11]

Heavy resistance exercise has been shown to acutely potentiate muscle force output, at least when a comprehensive task-specific warm-up is not completed,[2,8,12] however force production can also be reduced as a result of fatigue or coordination interference (i.e. perseveration) processes, which may mask any potentiating effects.[1] Some studies have reported that vertical jump performance enhancements can be detected after only 20 s[13] and 90 s[14] following maximal isometric squats and heavy box squats, respectively. Findings from these studies are indicative that effects may be detected within the time course of "classic" PAP observed using muscle twitch examinations.[8] Nonetheless, a meta-analysis of the literature revealed that minimal performance enhancement was likely when the rest period was less than 2 min, whereas longer rest periods of 3-7 min were more beneficial.[15] The equivocal findings likely result from disparate study methodologies including types of conditioning activity (i.e. movement-pattern specificity), performance tasks, delay between the conditioning activity and performance testing, study participant characteristics (e.g. experienced/novice lifters) and warm-up performed, which limit our understanding of the potentiating effects of these warm-up strategies.

The countermovement vertical jump (CMJ) task is commonly performed in sport but is also a model commonly used to test power and muscle function in clinical research environment. Various high-intensity exercise types have been performed before maximal CMJ tests including resistance-, plyometric-, and electrical muscle stimulation-based exercises.[16,18] The back squat exercise is a fundamental exercise for the development of lower-limb strength and power[12] and its use during a warm-up has been reported to improve subsequent functional performance including CMJ height;[1,4] this enhancement is commonly attributed to the PAP effect. However, maximal voluntary muscle activity occurs only during a short period in the early ascending (concentric) phase, near the “sticking point” in successful maximal (1-RM) back squat attempts. The larger internal and smaller external moment arms developed at the hip and knee joints (resulting in a greater mechanical advantage) combined with the optimized force-length characteristics of lower-limb muscles, ensures that only a submaximal muscle activation is needed for successful completion of the remaining part of the lift.[18] Thus, theoretically, variations of the exercise that evoke a greater muscle activation throughout the lift could result in a greater warm-up (i.e. PAPE) effect and improve CMJ performance. A possible means to alter the loading characteristics of the squat lift is the use of elastic bands to reduce the external load in the deepest part of the squat while increasing external load when the joints are more extended, the internal moment arms are greater and optimal muscle lengths are achieved.[18,19] Previous studies comparing elastic bands to free-weight squats for muscle activities (EMG), kinematics and kinetics has shown significantly higher EMG, movement velocity, and external power in the first quarter of the eccentric phase and the last quarter of the concentric phase of the squat exercise when using elastic bands.[19] Accordingly, it has been found that preconditioning contractions using elastic bands significantly increased subsequent 1-RM squat test performance without detectable changes in knee extensor muscle activity or knee flexion angle, although eccentric and concentric velocities were reduced.[2]

Accordingly, elastic bands can be used to increase resistance in ranges of motion where the muscles can produce the greatest relative force as well as unload the system where muscle forces are compromized, and thus allow a larger overall impulse to be produced. Given the possibility for higher muscle activation and greater total work done during the lift, it might be hypothesized that these conditions would allow for a greater potentiating effect.

Individuals incorporating the use of elastic band-based strategies into a warm-up routine may observe an acute enhancement of performance, and thus benefit from a greater mechanical stimulus during training.[2] However, a common limitation in the literature is that minimal or no warm-up has been provided before imposing the conditioning activity[8] limiting the comprehensive applicability and external validity of the data. Therefore, the purpose of this study was to compare the influence of free-weight resistance (FWR) and variable resistance (VR; imposed through elastic bands) squat exercises following a task-specific comprehensive warm-up on subsequent CMJ performance at different post-conditioning time points (i.e. 30 s, 4 min, 8 min, and 12 min). It was hypothesized that (i) FWR and VR would enhance subsequent CMJ performance; however the variation in resistance imposed by the elastic bands during the squat lift would (ii) further enhance subsequent CMJ performance, (iii) alter CMJ kinetic and kinematic parameters (i.e. peak power, peak eccentric kinetic energy, impulse- and time-based descent-to-ascent asymmetry indexes, vertical stiffness (K_{vert}), rate of force development (RFD), hip, knee and ankle joint kinematics), and (iv) increase the muscle activity of the lower-limb extensor muscles more than squatting without elastic bands.

MATERIALS AND METHODS

Participants

Fifteen active men (age = 21.7 ± 1.1 y, height = 1.8 ± 1.9 m, mass = 77.6 ± 2.6 kg) with ≥5 y experience with heavy weight training of varying levels (from regional to elite) and training backgrounds volunteered to participate after providing written informed consent and completing a pre-test medical questionnaire. The participants' training protocols involved resistance training, sprint running, power exercises, dynamic/explosive exercises, agility drills and other specific exercises relevant to their sports. The participants had no recent illness or lower-limb injury, were instructed to maintain normal eating and drinking habits throughout the study, and avoided strenuous exercise and stimulant use at least 48 h prior to testing. Ethical approval was granted by the ethics committee at the University of Thessaly, Greece, with the study conducted in accordance with the Declaration of Helsinki. Effect size (ES) values (Cohen's *d*) were calculated from mean changes in variables (jump height, power, RFD and EMG) from previous studies using similar methods. To ensure an adequate population to reach statistical power (set at 0.8) was recruited, effect sizes were initially calculated from related research[21-23] for jump height (ES = 1.48), power (ES = 1.0), RFD (ES = 1.29), and EMG (ES = 1.2). To ensure an adequate sample, the measure with the smallest ES (power, 1.0) was used to calculate sample size. The analysis revealed that the initial sample size required for statistical power was 14; thus, considering the possibility of participant withdrawal and data loss, 18 participants were recruited with 15 participants completing the study.

Protocol

Overview

A randomized, cross-over design was implemented to compare CMJ performance following two warm-up conditions: free-weight resistance (FWR) or variable resistance (VR) back squat exercise. Participants completed a familiarization session one week prior to the two experimental sessions, each separated by 72 h and performed at the same time of the day. During familiarization, anthropometric characteristics were recorded, one-repetition maximum (1-RM) back squat load was determined, and the participants were familiarized with all experimental procedures. During experimental conditions, following the comprehensive task-specific warm-up (described later), the participants performed three pre-intervention CMJs followed by back squats at 85% of 1-RM using either FWR or VR warm-up. CMJ trials were then performed at 30 s, 4 min, 8 min and 12 min after the intervention. Peak power output, peak eccentric kinetic energy, impulse- and time-based descent-to-ascent asymmetry indexes, peak normalized (to body weight) K_{vert} and RFD, peak knee flexion angle, peak eccentric and concentric knee angular velocities, peak and mean eccentric and concentric electromyograms (EMG; vastus lateralis (VL), vastus medialis (VM), gluteus maximus (Glut)), and jump height were measured during all CMJ trials (described later).

Familiarization session and one-repetition (1-RM) squat lift test

The 1-RM back squat protocol was adopted from Sheppard and Triplett et al.[24] Participants initially performed a 5 min cycling warm-up (Monark 874E, Varberg, Sweden) at 65 rpm with a 1-kg resistance load followed 2 min later by 2 sets of 10 back squat repetitions using an unloaded 20-kg Olympic bar. The participants then completed 8-10 repetitions of the squat lift exercise at 50% of their estimated 1-RM load before the load was increased by 20% for 3-5 repetitions, and by a further 20% for 2-3 repetitions with a 2 min rest between sets. The load was finally increased by 5% movements with 2-4 min rest between lifts until participants failed to complete the lift; the previous successful attempt was recorded as their 1-RM load. To ensure correct technique, participants were instructed to place the bar above the posterior deltoids at the base of the neck and position the feet shoulder width apart with the toes pointed slightly outward and attempt to squat to a position where the knee was flexed to ∼90° before returning to a standing position. This was visually assessed by an experienced, certified British Amateur Weight Lifting Association (BAWLA) spotter throughout all testing procedures to ensure correct technique and safety during the lifts, with participants receiving strong verbal encouragement to promote maximal effort.

Comprehensive task-specific warm-up and countermovement jump trials

During the experimental trials the participants performed a comprehensive task-specific warm-up consisting of 5 min of cycling followed by five continuous unloaded squats (i.e. non-jumping) at a rhythm of 2 s/ 2 s (eccentric/concentric) and a further 5 squats at a rhythm of 1 s/ 1 s after a 30 s rest. After 20-s rest, five continuous CMJs were performed at ~70% of the participants' perceived maximum and, after a further 30 s rest, maximal CMJs were performed every 30 s until three consecutive jumps were within 3% of jump height (4-7 jumps were performed in all trials). The CMJ was performed from a stationary upright standing position with hands positioned on the hips, making a preliminary downward movement with the hips and knees flexed, and immediately jumping vertically up as high possible.[12]

Two minutes after the completion of the warm-up, three maximal pre-intervention CMJ trials were performed to establish baseline (i.e. after warm-up) performance. A conditioning set of three repetitions of back squats at 85% of the previously determined 1-RM using either FWR or VR (described later) was then performed before the participants completed three CMJs 30 s, 4 min, 8 min and 12 min (see Table 1) later with participants receiving verbal encouragement to jump as high as possible. The post-intervention intervals were selected from previous data describing the time-course of the performance augmentation (PAP) response.[21,25]

Table 1 about here

Conditioning activities: free-weight resistance (FWR) and variable resistance (VR)

During the FWR condition, the load was adjusted to 85% of the previously determined 1-RM load with the participants performing one set of three-repetition back squats. In the VR warm-up condition, 35% of the total load was generated from band resistance. To ensure a similar load of 85% 1-RM across FWR and VR conditions, mechanical properties of the bands were determined to allow the band resistance to generate 35% of the total load. Half of the band's resistance was subtracted from the total free-weight load to ensure the elastic bands did not have substantially different average resistance compared with the FWR condition, thus both the FWR and VR warm-up conditions were equalized, as previously reported.[20,22] The participants stood on a force platform with 85% 1-RM load to determine the combined load (kg), the bar was then unloaded to adjust the band tension. The elastic bands were anchored to the floor with custom-made weight stands and attached equidistant to the ends of the Olympic bar to ensure the participant's stability. The thickness and lengths of the elastic bands were adjusted so that: (i) the tension in the bands increased the ground reaction force (measured by force platform) by 35% of the 85% load when the participants were standing, but (ii) bands were slack in a full squatting position and thus provided no additional loading. The linear force-length properties of the bands ensured, therefore, that the average load during the lift equated to 35% of the total load. For example, a 100-kg load in the FWR condition would require 35-kg (35%) to be generated from the bands. Half of the 35-kg load (i.e. 17.5 kg) was removed from the bar with the 35-kg resistance added from the bands providing a total load of 117.5 kg in the standing position. As band tension reduced as the participant squats, 35 kg of load was removed leaving the 82.5 kg from the bar in the full squatted position. Thus, the average loading throughout the lift in this example is 100 kg, identical to the FWR condition whilst enabling 35% to be generated by band tension.

Kinetic and kinematic analyses

Kinematic data were collected during the CMJs using a Vicon motion analysis system (T-Series, Oxford Metrics LTDA, Oxford, UK) with 10 cameras operating at 100 Hz surrounding two force platforms (Bertec, FP4060-10-2000, Bertec Corporation, Columbus, OH, USA). Ground reaction forces were sampled at 1000 Hz and time-synchronized with the Vicon system (see Figure 1). The data were then filtered using Woltring's quantic spline algorithm[26] with a mean squared error setting of 15 before running the Plug-In-Gait biomechanical model (Vicon Plug-in-Gait, Oxford Metrics). The procedures identified by Davis et al.[27] were followed to define Cardan angles and to reconstruct a system of embedded coordinates from the marker set to 0° at the three joints of the lower extremities (hip, knee and ankle) in a standing position. Lower-limb kinetic and kinematic data were captured by placing 16 reflective markers over the pelvis, left and right thigh, left and right shank in a straight line, and the left and right foot at a right angle to the leg. Data were analyzed using Vicon Nexus (v.2.3) software to determine peak hip, knee and ankle flexion angle and angular velocity data during the pre- and post-intervention CMJ trials (see Figure 1).

Figure 1 about here

All jumps were performed from the standing position with each foot in parallel on two force platforms providing a separate yet time-synchronized measurement of the force data for each leg. The participant's body weight was calculated by averaging the vertical force from each platform when the participants were stationary. The initiation of the jump (i.e. the beginning of the eccentric phase) was identified as the point when the ground reaction force (N) decreased 2 standard deviations (SD) below the mean baseline force. The vertical ground reaction force was integrated using the trapezoid method during the eccentric and concentric phases of the jump. The net impulse was calculated independently and summed from the left and right force platforms. Ground reaction forces were directly quantified by integrating the applied force over time (i.e. impulse), which is equivalent to the change in momentum of the body:

$$J = \int F \, dt = \Delta p$$

where J = impulse, F = force, t = time and Δp = change in momentum.

The take-off velocity was determined from impulse by dividing by body mass, and the jump height was calculated using standard equations for motion.[28] To calculate power, the impulse-momentum approach was used. Since the force, mass and initial velocity conditions were known, instantaneous velocity could be calculated. The instantaneous power was calculated as force $\times$ velocity and the peak values were determined for the propulsive phase of the CMJ:

$$V_{(0)} = 0$$

$$F(\mathrm{i})t = m(v_{(\mathrm{i}+1)} - v_{(\mathrm{i})})$$

$$\Delta v = (F_{(\mathrm{i})}t)/m$$

$$P_{(\mathrm{i})} = F_{(\mathrm{i})} \times V_{(\mathrm{i})}$$

where F = force, t = 1/sampling frequency, m = mass of body, load, v = velocity, and P = power.

The peak eccentric kinetic energy (KE) developed during the jumps was calculated as:

$$KE = ½mv^2$$

where m is the participant's mass and v is the velocity of the countermovement phase.

The impulse-based asymmetry index was calculated by dividing the negative and positive impulses, where the negative impulse describes the impulse that negatively accelerates the body downwards and the positive impulse accelerates the body upwards. The index was calculated to estimate the efficiency of the metabolic energy conversion into mechanical work (i.e. storage of elastic energy during eccentric contraction) performed during the CMJ from the force applied by the body to the ground[29] and subsequently released energy during the concentric phase of the SSC. The time-based asymmetry index was calculated as the quotient of times A + B, where A is the time from force first rising above 1 body weight to the peak vertical force and B is the time from peak force until force drops below 1 body weight. K_{vert} was calculated by dividing the peak vertical ground reaction force by the maximal vertical displacement of the center of mass during contact with the ground[30]

$$K_{vert} = F_{max} / \Delta y$$

where F_{max} = maximum vertical force, and Δy = maximum vertical displacement of the center of mass. The vertical displacement was determined by the double integration of the vertical force trace according to methods of Cavagna.[31]

The peak RFD (normalized to body weight) was calculated from the initiation of the jump (i.e. first rise in force during the eccentric phase) using the average force-time curve with a 50-ms time window.

Muscle activity (electromyography; EMG)

EMG data were collected wirelessly using a Myon MA-320 EMG system (Myon AG, Schwarzenberg, Switzerland) from vastus lateralis (VL), vastus medialis (VM) and gluteus maximus (Glut). The skin was shaved, abraded and cleansed with alcohol before bipolar adhesive surface electrodes (Noraxon Dual Electrodes, Ag-AgCl, Noraxon USA, Inc, Scottsdale, AZ) were placed over the muscle belly with an inter-electrode distance of 2 cm according to SENIAM guidelines. EMG data were sampled at 2000 Hz and imported into ProEMG software (version 4.1) and filtered using a Butterworth (20-500 Hz bandpass) filter before using a symmetric moving root-mean-square algorithm with a 50-ms sampling window. The Myon EMG software was integrated with an optimal tracking device for synchronization between the systems (Vicon motion analysis system, Oxford, UK). The normalized EMG amplitude during isometric squat lifts (% maximal voluntary contraction [MVC]) for each muscle was used as a measure of neuromuscular activity during the jumps (see Figure 1), with peak and mean EMG activity recorded during the eccentric and concentric phases.

Data analyses

All data were analyzed using SPSS statistical software (version 24.0; IBM, Chicago, IL, USA); all data are presented as mean ± SE. Normal distribution was assessed using Shapiro-Wilks test; no significant difference ($p > 0.05$) was detected in any variable indicating that all data sets were normally distributed. Separate multivariate analyses of variance (MANOVAs) were used to compare (a) jump height and peak power, and (b) EMG. Where significant differences were detected, separate two-way repeated measures ANOVAs (time × condition) were used to determine differences in (a) jump height, (b) peak power, (c) peak eccentric kinetic energy, (d) impulse- and time-based descent-to-ascent asymmetry indexes, (e) peak normalized RFD, (f) peak hip, knee and ankle flexion angle, (g) peak eccentric and concentric hip, knee and ankle angular velocities, (h) peak and mean eccentric and concentric EMG activities during CMJ trials. Significance was accepted at $p < 0.05$ for all tests.

Reliability

Reliability for all measures was determined during the pre-intervention vertical jumps from the VR and FWR warm-up conditions. No significant differences ($p > 0.05$) were detected in any measure and high intraclass correlation coefficients (ICCs) calculated for jump height (0.95), peak power (0.98), peak eccentric kinetic energy (0.99), impulse- (0.96) and time-based (0.91) asymmetry indexes, K_{vert} (0.81), peak RFD to 50 ms (0.92), peak hip, knee and ankle flexion angle ranged from 0.67 to 0.96, peak angular velocities ranged from 0.76, 0.95, 0.85 to 0.85, 0.95 0.79 for hip, knee and ankle, respectively. ICCs for the EMG data ranged from 0.73 to 0.89, 0.85 to 0.92, 0.85 to 0.92 for VL, VM and Glut, respectively. Coefficients of variation

(CoV) expressed as a percentage of the mean were also calculated for jump height (8.0%), peak power (6.2%), peak eccentric kinetic energy (8.5%), impulse- (4.9%), and time-based (14.6%) asymmetry indexes, K_{vert} (8.7%), peak RFD to 50 ms (12.5%), peak hip, knee and ankle flexion angle ranged from 3.8% to 7.6%, peak angular velocities ranged from 5.6%, 5.2%, 14.8% to 5.0%, 3.4%, 6.3% for hip, knee and ankle, respectively. CoVs for EMG data 9.0% to 14.3%, 11.3% to 14.1%, 14.9% to 22% for VL, VM and Glut, respectively.

RESULTS

In the FWR condition, no significant changes ($p > 0.05$) were found in jump height (range = 3.0 ± 2.0 % to 4.9 ± 2.2%) at any time point compared with pre-intervention data (see Figure 1). Also, no significant changes ($p > 0.05$) were observed in peak power (0.1 ± 2.4% to 3.6 ± 1.6%), peak eccentric kinetic energy (0.5 ± 4.6% to 4.9 ± 3.6%), impulse- (0.6 ± 1.6% to 2.0 ± 1.9%) and time-based (4.5 ± 7.0% to 14.8 ± 8.4%) asymmetry indexes, K_{vert} (3.1 ± 4.3% to 5.8 ± 4.1%) or peak normalized RFD (3.1 ± 6.1% to 11.8 ± 8.4%) at any time point (see Table 2). No changes ($p > 0.05$) were detected in peak eccentric hip (0.5 ± 1.7% to 2.6 ± 1.9%), knee (0.5 ± 2.1% to 2.6 ± 2.2%), ankle (2.2 ± 5.4% to 9.0 ± 5.0%) or concentric hip (1.2 ± 2.1% to 3.7 ± 2.0%), knee (0.5 ± 1.7% to 1.7 ± 2.0%), ankle (1.4 ± 2.1% to 4.7 ± 2.6%) angular velocities, or peak hip (1.5 ± 1.3° to 3.4 ± 1.2°), knee (0.1 ± 1.2° to 1.7 ± 1.9°), ankle (0.1 ± 0.6° to 0.6 ± 0.5°) flexion angle (see Table 3). Furthermore, no changes in peak or mean eccentric EMG eccentric activity ($p > 0.05$) in VL (peak = 2.4 ± 3.8% to 7.2 ± 5.2%; mean = 0.7 ± 6.4% to 7.3 ± 5.7%), VM (peak = 0.6 ± 3.2% to 8.3 ± 5.0%; mean = 8.9 ± 4.5% to 10.9 ± 3.2%), Glut (peak = 0.9 ± 6.0% to 8.7 ± 3.8%; mean = 2.3 ± 6.0% to 10.7 ± 7.4%) or concentric EMG in VL (peak = 0.4 ± 10.3% to 9.4 ± 8.3%; mean = 2.2 ± 8.6% to 7.0 ± 6.9%), VM (peak = 0.5 ± 4.6% to 7.1 ± 5.2%; mean = 1.2 ± 7.1% to 9.5 ± 5.4%) or Glut (peak = 1.3 ± 5.7% to 10.4 ± 5.6%; mean = 2.1 ± 6.6% to 8.3 ± 8.9%) were detected (see Table 4).

Table 2 about here

Figure 2 about here

In the VR condition, significant increases ($p < 0.05$) in CMJ height were detected at 30 s (5.9 ± 1.2%), 4 min (5.6 ± 1.8%), 8 min (6.5 ± 2.6%) and 12 min (5.3 ± 2.5%) time points compared with pre-intervention data (see Figure 2). Significant increases ($p < 0.05$) were also observed in peak power at 30 s (4.7 ± 1.2%), 4 min (5.9 ± 1.3%), 8 min (4.4 ± 1.7%) and 12 min (4.8 ± 1.7%) time points compared to pre-intervention data. These changes in CMJ height and power were also statistically different to FWR ($p < 0.05$). Similarly, significant increases ($p < 0.05$) were found in peak normalized RFD at 30 s (18.9 ± 7.8%), 4 min (12.9 ± 5.9%), 8 min (19.1 ± 5.0%) and 12 min (16.0 ± 8.1%) compared to pre-intervention data. However, no significant change ($p > 0.05$) in peak eccentric kinetic energy (0.4 ± 4.8% to 5.2 ± 4.8%) or impulse- (1.4 ± 1.5% to 4.6 ± 2.4%) or time-based (7.4 ± 11.7% to 13.0 ± 12.5%) asymmetry indexes, K_{vert} (6.6 ± 4.5% to 8.9 ± 3.7%) were found following the VR warm-up condition at any time point (see Table 2).

Table 3 about here

No significant change in peak hip (1.3 ± 1.3° to 1.9 ± 1.5°), knee (0.9 ± 2.9° to 4.1 ± 3.0°), ankle (0.9 ± 0.4° to 1.4 ± 0.7°) flexion angles were observed in VR at any time point. Similarly, no changes ($p > 0.05$) were found at any time point (see Table 3) in peak eccentric hip (0.2 ± 2.2% to 2.5 ± 2.2%), knee (0.04 ± 1.7% to 2.6 ± 2.5%), ankle (0.1 ± 6.6% to 6.7 ± 8.7%) or concentric hip (1.5 ± 2.4% to 3.6 ± 2.1%) or ankle (1.1 ± 2.0% to 3.5 ± 2.1%) angular velocities or peak or mean eccentric EMG amplitudes for VL (peak = 0.5 ± 4.3% to 3.1 ± 4.3%, mean =

4.9 ± 6.0% to 9.2 ± 6.5%), VM (peak = 2.1 ± 4.6% to 9.6 ± 4.0%, mean = 4.9 ± 5.4% to 6.7 ± 5.8%) or Glut (peak = 2.2 ± 6.3% to 4.6 ± 6.3%, mean = 3.5 ± 7.4% to 4.9 ± 6.5%). However, a significant increase ($p < 0.05$) was found in peak concentric knee angular velocity at 30 s (3.1 ± 1.4%), 4 min (4.1 ± 1.7%), 8 min (3.2 ± 1.0%) and 12 min (3.1 ± 1.5%) and mean concentric VL EMG activity at 30 s (28.1 ± 10.5%), 4 min (31.5 ± 11.0%), 8 min (33.4 ± 15.9%) and 12 min (27.5 ± 14.5%) compared to pre-intervention data. No changes ($p > 0.05$) in mean concentric VM (3.7 ± 8.0% to 12.7 ± 8.6%) or Glut (0.3 ± 10.4% to 7.0 ± 7.5%) EMG or peak concentric VL (0.6 ± 5.8% to 4.5 ± 4.7%), VM (0.3 ± 5.1% to 9.2 ± 4.1%) or Glut (0.2 ± 9.2% to 7.1 ± 7.7%) EMG were observed at any time point (see Table 4).

Table 4 about here

Significant ($p < 0.05$) correlations were observed between the change in CMJ height (pre-intervention to 8 min post-intervention, i.e. where the greatest mean increase in jump height occurred) and changes in peak power (r = 0.82) during VR. No significant correlations ($p > 0.05$) were found between change in CMJ height and changes in peak normalized RFD (r = 0.27), peak knee angular velocity (r = -0.21), mean concentric VL EMG (r = 0.17) or peak eccentric kinetic energy (r = 0.32).

DISCUSSION

The primary aim of the present study was to assess the magnitude and time-course of changes in countermovement vertical jump (CMJ) performance after traditional free-weight (FWR) and variable (VR) resistance squat exercises were performed following a comprehensive task-specific, warm-up routine. The first hypothesis can be partially accepted as the lack of change in any measure following the FWR condition suggests that no additional benefit (i.e.

PAP/PAPE effect) was derived from the inclusion of intense loading from FWR exercise (i.e. the conditioning activity), contrary to the improvement in jump height following the use of elastic bands. This finding contrasts those of previous studies where the performance of heavy squat lifts increased CMJ height,[21,32] and other literature reporting an increase in tasks including sprint running performance.[33] However, those previous studies either did not report the use of other warm-up activities or only included a light cardiovascular warm-up rather than a more comprehensive task-specific warm-up including progressively intense task-specific muscular contractions. The current finding of a lack of effect of a back squat conditioning activity after a comprehensive task-specific warm-up (see Figure 2) is, however, consistent with a previous report of an absence of change in vertical jump performance when dynamic warm-up exercises were employed prior to a set of back squats.[17] These data are indicative that a lack of a comprehensive task-specific warm-up may enable further augmentation of performance after squats were performed, but may be of limited relevance to athletes, strength trainers and recreational exercisers who would customarily perform a thorough warm-up. That is, the high-intensity conditioning activities might only increase performance when the warm-up would otherwise be insufficient to promote maximal performance. Collectively, these findings indicate that the previously reported ‘potentiating’ effects of heavy free-weight back squat exercise on subsequent CMJ performance[16,21] may be a consequence of study design, where the limited use of warm-up protocols provided an opportunity for further performance augmentation after the baseline tests. Furthermore, inconsistencies in PAP responses[12,16,17] may depend on fatigue-potentiation or perseveration-potentiation interactions and their influence on subsequent performance therefore new strategies for designing warm-up protocols and optimal recovery periods following conditioning contractions are vital in order to induce a potentiation effect.

Despite FWR squat lifts having no effect on CMJ performance, a significant increase in jump height was achieved following the VR conditioning activity at all time points (30 s, 4 min, 8 min and 12 min; see Figure 2), which suggests a prolonged 'potentiating' effect was evoked, i.e. post-activation performance enhancement; PAPE.[9] Thus, the second experimental hypothesis, that jump height would be increased following the VR intervention, can be accepted. These data are consistent with a previous study[34] in which box squats incorporating elastic band resistance acutely increased power output during subsequent CMJ tasks. However, in the present study it was shown that this effect can be evoked even after completion of a comprehensive task-specific warm-up, which was not included in previous studies. Although each maximal CMJ may possibly potentiate the next one, no significant improvement occurred in the FWR condition, therefore these jumps were unlikely to explain the increased performance in VR. Previous studies showed that only seconds or a few minutes are needed to recover from a short bout of maximal-effort exercise (e.g. less than 1 min for recovery from a maximal squat[35] or bench press lifts[36]), thus it is unlikely that fatigue is a factor influencing the findings of the present study as a significant increase was observed across all time points. The use of elastic bands reduces the effective load near the "sticking point" in the early concentric phase of the squat lift but then allows for greater loading later in the lift as the effective mechanical advantage is increased.[2] The ability for muscles to operate closer to their maximum force capacity through a greater proportion of the lift may therefore enhance subsequent muscle force output and elicit a greater dynamic muscle performance (i.e. increase in CMJ height), even when a comprehensive task-specific warm-up is already completed. Collectively, these data indicate that the use of elastic bands, which alter the loading strategy during the lift, provides a more effective warm-up than either warm-up alone or warm-up that also includes traditional free-weight resistance exercises.

In the present study significant changes in force production (peak power and RFD; see Table 2) at all time points in the VR warm-up condition were consistent with the changes in jump height. However, peak hip, knee and ankle, flexion angle, peak eccentric kinetic energy, the impulse- and time-based asymmetry indexes remained unchanged and no change was detected in K_{vert} (see Tables 2 and 3), which is consistent with previous research.[30] Accordingly, changes in jump kinematics cannot explain the changes in force production or jump height. The third hypothesis, that both kinetic and kinematic parameters would be altered by elastic band-resisted squat lifts, can therefore only be partially accepted. The changes in peak jump power were significantly correlated with the changes in CMJ height, however a poor relationship was identified between changes in RFD and CMJ height. This latter finding is consistent with a previous report[37] in which stretch-shortening cycle test performances were not statistically related to RFD measured during the test. The poor relationship may be partly explained by the participants being well strength-trained yet relatively untrained in explosive power-based exercises, and thus unable to rapidly reach peak force.[38] However, further research on power-trained athletes is needed to fully elucidate the importance of training status.

A number of mechanisms relating to stretch-shorten cycle efficiency may have contributed to the increased jump height, including a more rapid muscle stretch resulting from force potentiation,[3939] greater elastic energy storage in the muscle,[40] an increased time of muscle activation,[40,41] an augmented pre-load effect,[42] force and stiffness augmentation from stretch reflexes,[41] or changes in relative contributions of muscle and tendon allowing the muscle to operate at lower shortening speeds and over shorter distances.[43] Whilst it is difficult to assess the effects of each, the peak eccentric kinetic energy and both impulse- and time-based asymmetry indexes remained unchanged after VR, indicating that the total energy available for storage in elastic structures (eccentric kinetic energy), the kinematic pattern adopted to make use of it (asymmetry indexes),[29] and the time for force application and likely contribution of stretch reflexes, were also unchanged. Nonetheless, increases in peak power and concentric knee angular velocity were observed.

Nonetheless, a more plausible explanation for the increase in force production, and thus jump height, may be found in the increased knee extensor muscle activity detected in the concentric phase (VL EMG increased 27.5-33.4% across time points; see Table 4). Thus, the fourth hypothesis, that extensor muscle activity would be increased, can be accepted. The greater increase in EMG activity in VL than VM or Glut is consistent with previous reports of greater VL EMG in the concentric phase of a CMJ after both low- and moderate-intensity squat warm-ups[32] and would likely have resulted from an increased motor unit firing frequency.[44] In fact, Nikolaidou et al.[45] found that a greater jump height was achieved during CMJ compared to squat jump which was consistent with an increased VL activation during the push off phase. Increased phosphorylation of the myosin light chain leading to an increase in myofilament Ca^{2+} sensitivity and force output (i.e. classic PAP) may have contributed to the increase in CMJ, although it resolves completely within about 5 min[11] thus its effect at 4 – 12 min would have been negligible. Although other mechanisms such as increases in muscle temperature[5] (not examined in the present study) may have contributed to the increase in jump height it remains likely that the change in muscle activation was the major factor influencing the improvement in CMJ performance. The increased muscle activity and consequent increase in peak power output in the concentric phase would have allowed a greater jump height without changes in kinematics or stretch-shorten cycle efficiency (i.e. without changes in eccentric knee angular velocity, eccentric kinetic energy, impulse- and time-based asymmetry indexes or K_{vert}). The most likely explanation for the finding is that the variation in muscle force requirements imposed by the use of elastic band resistance influenced muscle recruitment patterns and ultimately increased concentric force output.[19] The current findings hint at the possibility that manipulation of loading strategies during warm-up exercises might beneficially alter muscle recruitment amplitude or timing and result in greater performances than achieved through traditional high-intensity, task-specific warm-ups alone. This hypothesis should be explicitly examined in future studies. It is important to note that it was not possible to measure muscle temperatures in the current study. However, muscle temperature would likely have increased substantially during the comprehensive task-specific warm-up so temperature may have remained constant (i.e. in an optimum zone) for a longer time, and any further small increase in temperature from the conditioning activities would have been similar between conditions. This may have allowed the improved muscle activation to result in a greater jump performance and for the increased activation to persist for a longer time. Thus, although it remains to be explicitly examined in future, it can be considered unlikely that muscle temperature differences could explain the between-condition differences in jump performance.

PERSPECTIVE

The completion of brief, high-load free-weight squat exercise following a comprehensive task-specific warm-up failed to alter CMJ height, force/power production or movement pattern. These findings are suggestive that the previously-observed ‘potentiating’ effect of squat exercise may be a consequence of limited warm-up. The beneficial effect of a free-weight squat strategy to potentiate the system may therefore, be minimal in athletic populations that typically perform high-intensity, task-specific warm-up routines prior to maximal exercise tasks. However, the use of elastic band resistance during these squats resulted in significant increases in jump height, peak power, peak concentric knee angular velocity and peak RFD, as well as increased VL EMG activity in the concentric (propulsive) phase of the jump, which did not return to baseline after 12 min despite a comprehensive task-specific warm-up being completed. The results suggest that the inclusion of tasks in which force-time parameters differ from the outcome task (CMJ in the current study) might evoke positive acute adaptations in addition to those achieved through warm-up alone. Further research is required to determine whether similar effects are observed following different warm-up strategies and in different athletic tasks, as well as in other populations.

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TABLE AND FIGURE LEGENDS

Table 1. Study design timeline. Acronyms: CMJ = countermovement vertical jump; FWR = free-weight resistance; VR = variable resistance.

Table 2. Kinetic measures of vertical jump performance across all time points following the free-weight resistance and elastic band warm-up conditions (values are reported as mean ± SE; *$p < 0.05$ compared to pre-intervention and FWR condition). Acronyms: Pre = pre-intervention; FWR = free-weight resistance; VR = variable resistance; K_{vert} = vertical stiffness; RFD = rate of force development.

Table 3. Kinematic measures of vertical jump performance across all time points following the free-weight resistance and elastic band warm-up conditions (values are reported as mean ± SE; *$p < 0.05$ compared to pre-intervention). Acronyms: Pre = pre-intervention; FWR = free-weight resistance; VR = variable resistance; ECC = eccentric; CON = concentric.

Table 4. Normalized mean and peak VL, VM and Glut EMG amplitudes measured during vertical jumps across all time points following free-weight resistance and elastic band warm-up squat conditions (values are reported as mean ± SE; *$p < 0.05$ compared to pre-intervention and FWR condition). Acronyms: VL = vastus lateralis; VM = vastus medialis; Glut = gluteus maximum; EMG = electromyogram; MVC = maximum voluntary contraction; FWR = free-weight resistance; VR = variable resistance; ECC = eccentric; CON = concentric.

Figure 1. Exemplar data from a subject depicting CMJ height, ground reaction force, knee angular velocity, knee flexion angle and VL EMG activity at 8 min following the free-weight resistance and elastic band warm-up squat conditions. VL = vastus lateralis; CMJ = countermovement vertical jump; FWR = free-weight resistance; VR = variable resistance.

Figure 2. Mean countermovement vertical jump height following free-weight resistance and elastic band warm-up squat conditions. *Significant increases (5.3-6.5%; $p < 0.05$) in vertical jump performance were achieved across all time points following the VR warm-up condition compared to pre-intervention and the FWR warm-up condition. Pre = pre-intervention; FWR = free-weight resistance; VR = variable resistance.

Table 1. Study design timeline.

Task	Time (min)
5-min cycle	0-5.0
5 unloaded squats (1 s/ 1 s)	5.0-6.0
5 unloaded squats (2 s/ 2 s)	6.0-7.0
5 CMJs (70%)	7.5-8.5
Single CMJs every 30 s (100%)	9.0-11.0
CMJ Test 1	13.0-13-5
FWR or VR squats	14.5-15.0
CMJ Tests (2-5)	15.5, 19.5, 23.5, 27.5

Acronyms: CMJ = countermovement vertical jump; FWR = free-weight resistance; VR = variable resistance.

Table 2. Kinetic measures of vertical jump performance across all time points following the free-weight and variable resistance warm-up conditions (values are reported as mean ± SE; *$p < 0.05$ compared to pre-intervention and FWR condition).

Measure	Condition	Pre	30 s	4 min	8 min	12 min
Peak Power (W)	FWR	49.3 ± 1.9	50.3 ± 1.5	50.8 ± 1.7	49.2 ± 2.2	50.3 ± 1.7
	VR	49.0 ± 1.7	51.3 ± 1.8*	51.8 ± 1.6*	51.0 ± 1.7*	51.2 ± 1.7*
Peak Eccentric Kinetic Energy (J)	FWR	87.4 ± 7.7	95.8 ± 9.0	90.8 ± 9.4	90.3 ± 7.7	88.0 ± 9.0
	VR	94.3 ± 8.0	93.6 ± 7.3	87.9 ± 7.2	88.8 ± 6.9	82.4 ± 5.9
Impulse asymmetry index (N·s)	FWR	2.9 ± 0.1	2.8 ± 0.1	2.9 ± 0.1	2.9 ± 0.1	2.9 ± 0.1
	VR	2.8 ± 0.1	2.9 ± 0.1	2.9 ± 0.1	2.9 ± 0.1	2.9 ± 0.1
Time asymmetry index (ms)	FWR	1.5 ± 0.1	1.4 ± 0.2	1.5 ± 0.2	1.3 ± 0.2	1.2 ± 0.2
	VR	1.4 ± 0.2	1.5 ± 0.2	1.1 ± 0.2	1.4 ± 0.2	1.2 ± 0.2
K_{vert} ($N \cdot m^{-1} \cdot kg^{-1}$)	FWR	70.8 ± 6.0	72.6 ± 3.8	70.5 ± 3.6	69.0 ± 3.7	72.0 ± 3.8
	VR	69.9 ± 5.0	73.3 ± 3.9	73.5 ± 4.5	74.6 ± 3.7	74.4 ± 4.5
Peak normalized RFD ($N \cdot s^{-1}$)	FWR	134.2 ± 11.3	147.1 ± 12.2	132.5 ± 10.8	141.8 ± 13.5	118.2 ± 7.5
	VR	126.1 ± 6.7	149.8 ± 12.8*	143.2 ± 11.7*	149.2 ± 9.0*	147.7 ± 13.7*

Acronyms: Pre = pre-intervention; FWR = free-weight resistance; VR = variable resistance; K_{vert} = vertical stiffness; RFD = rate of force development.

Table 3. Kinematic measures of vertical jump performance across all time points following the free-weight and variable resistance warm-up conditions (values are reported as mean ± SE; *$p < 0.05$ compared to pre-intervention).

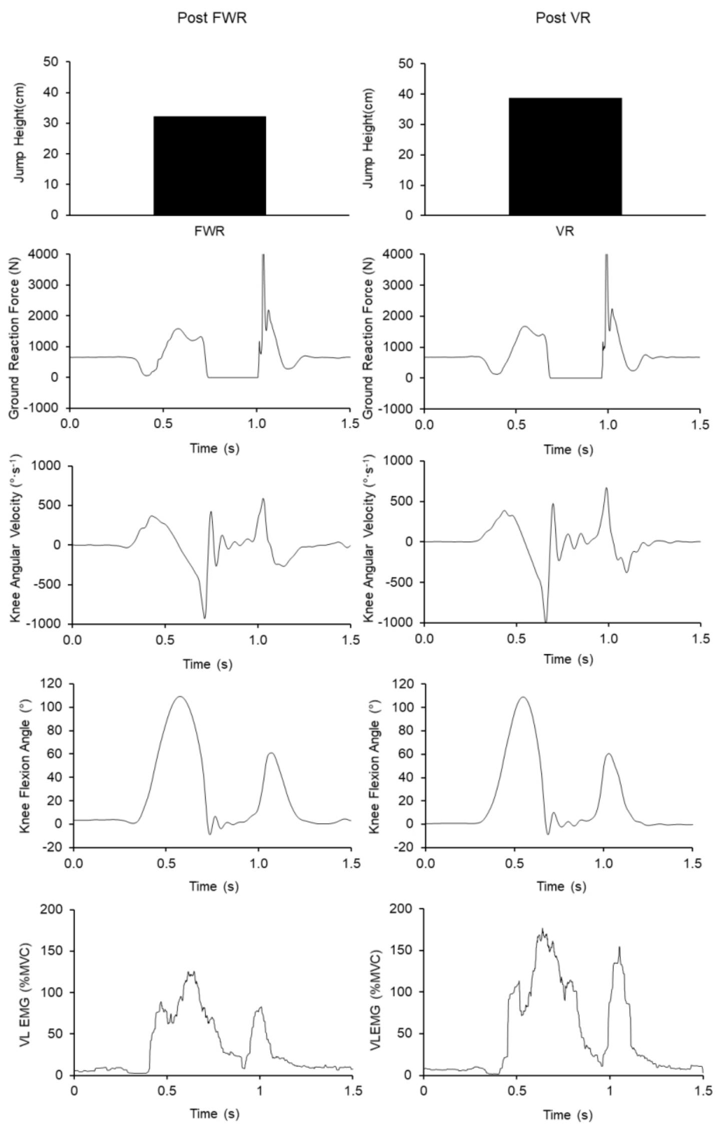
Measure	Mode	Condition	Pre	30 s	4 min	8 min	12 min
Peak hip angular velocity (°·s^{-1})	ECC	FWR	301.1 ± 9.5	302.2 ± 10.0	294.4 ± 9.8	291.4 ± 6.9	292.8 ± 9.2
		VR	298.2 ± 7.1	305.2 ± 8.3	300.2 ± 8.3	302.6 ± 8.8	297.3 ± 8.7
	CON	FWR	584.6 ± 15.6	605.4 ± 18.8	591.9 ± 20.2	575.7 ± 20.7	576.2 ± 15.8
		VR	572.2 ± 17.1	591.9 ± 20.2	593.0 ± 22.1	588.2 ± 19.3	580.8 ± 21.7
Peak knee angular velocity (°·s^{-1})	ECC	FWR	343.2 ± 13.6	341.0 ± 11.4	332.6 ± 11.9	343.8 ± 13.7	340.5 ± 14.3
		VR	352.1 ± 14.3	364.9 ± 15.7	353.5 ± 13.9	363.0 ± 15.0	347.5 ± 16.6
	CON	FWR	956.4 ± 23.6	971.6 ± 24.6	969.3 ± 26.7	939.6 ± 27.9	959.6 ± 25.1
		VR	937.0 ± 23.8	966.0 ± 28.8*	975.7 ± 29.7*	966.9 ± 26.2*	964.2 ± 24.5*
Peak ankle angular velocity (°·s^{-1})	ECC	FWR	108.1 ± 10.0	117.6 ± 12.0	109.7 ± 12.2	112.0 ± 10.9	114.4 ± 10.8
		VR	121.1 ± 12.8	118.7 ± 9.8	120.3 ± 9.0	112.8 ± 7.1	104.5 ± 5.0
	CON	FWR	745.4 ± 23.4	733.7 ± 25.5	728.2 ± 18.9	707.9 ± 25.3	721.5 ± 27.0
		VR	717.9 ± 21.3	723.6 ± 22.2	731.7 ± 23.6	735.1 ± 28.1	739.4 ± 19.1
Peak hip flexion angle (°)		FWR	79.3 ± 2.0	82.7 ± 2.1	81.8 ± 1.7	82.1 ± 2.4	81.8 ± 2.2
		VR	81.5 ± 1.9	83.2 ± 1.4	83.3 ± 1.9	83.4 ± 1.5	82.8 ± 1.5
Peak knee flexion angle (°)		FWR	71.7 ± 2.9	73.3 ± 3.0	71.1 ± 2.8	72.0 ± 2.7	71.9 ± 3.3
		VR	71.8 ± 3.5	72.6 ± 3.4	74.2 ± 3.3	75.2 ± 2.8	75.4 ± 3.5
Peak ankle flexion angle (°)		FWR	32.7 ± 1.6	32.6 ± 1.4	32.7 ± 1.4	33.0 ± 1.4	33.2 ± 1.4
		VR	33.8 ± 1.6	34.7 ± 1.6	34.8 ± 1.6	35.2 ± 1.6	34.8 ± 1.8

Acronyms: Pre = pre-intervention; FWR = free-weight resistance; VR = variable resistance; ECC = eccentric; CON = concentric.

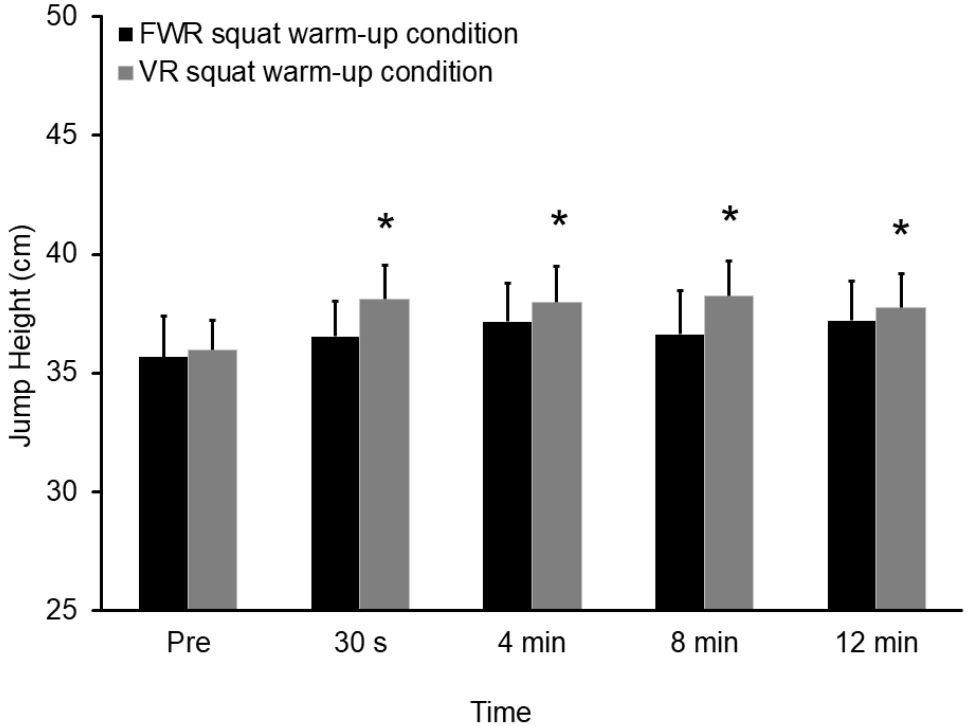
Table 4. Normalized mean and peak VL, VM and Glut EMG amplitudes measured during vertical jumps across all time points following free-weight and variable resistance warm-up squat conditions (values are reported as mean ± SE; *$p < 0.05$ compared to pre-intervention and FWR condition).

Measure	Mode	Condition	Pre	30 s	4 min	8 min	12 min
Mean VL EMG (%MVC)	ECC	FWR	31.9 ± 2.1	31.5 ± 3.4	30.5 ± 3.0	30.0 ± 2.0	29.5 ±2.9
		VR	28.5 ± 2.1	30.2 ± 2.2	31.9 ± 2.3	31.5 ± 1.8	32.0 ± 2.2
	CON	FWR	82.4 ± 6.1	83.9 ± 6.4	78.4 ± 8.5	72.5 ± 4.6	73.4 ± 6.0
		VR	85.4 ± 7.8	108.2 ± 13.3*	110.2 ± 12.2*	107.5 ± 10.5*	102.6 ± 9.4*
Peak VL EMG (%MVC)	ECC	FWR	89.2 ± 6.7	94.7 ± 8.0	90.4 ± 6.9	85.0 ± 6.7	84.0 ± 6.0
		VR	91.6 ± 4.9	95.0 ± 8.0	94.2 ± 6.1	90.7 ± 4.7	90.6 ± 5.9
	CON	FWR	112.4 ± 8.0	123.7 ± 9.6	116.9 ± 7.1	112.8 ± 6.7	112.2 ± 6.3
		VR	114.3 ± 5.8	115.8 ± 10.2	117.4 ± 7.6	111.2 ± 6.6	108.1 ± 6.6
Mean VM EMG (%MVC)	ECC	FWR	36.3 ± 2.7	33.9 ± 4.1	32.6 ± 3.3	32.2 ± 2.6	33.0 ± 3.4
		VR	37.9 ± 3.8	40.2 ± 3.8	38.1 ± 3.3	39.9 ± 2.9	38.1 ± 3.3
	CON	FWR	94.9 ± 5.0	95.3 ± 10.9	85.1 ± 8.4	85.1 ± 6.4	87.7 ± 7.3
		VR	90.2 ± 9.2	96.0 ± 7.9	94.7 ± 7.5	88.8 ± 5.9	87.2 ± 6.2
Peak VM EMG (%MVC)	ECC	FWR	98.6 ± 7.9	96.9 ± 7.4	92.9 ± 6.7	88.0 ± 6.1	89.0 ± 6.1
		VR	111.3 ± 9.5	114.4 ± 11.2	108.1 ± 10.2	104.7 ± 8.1	97.3 ± 6.7
	CON	FWR	132.0 ± 12.2	128.7 ± 11.5	120.5 ± 9.5	118.2 ± 8.6	118.8 ± 9.1
		VR	150.6 ± 12.8	149.0 ± 14.4	143.4 ± 12.5	140.8 ± 11.8	127.7 ± 8.9
Mean Glut EMG (%MVC)	ECC	FWR	20.0 ± 1.9	22.4 ± 2.8	21.3 ± 2.3	19.7 ± 1.7	21.2 ± 1.9
		VR	21.7 ± 2.5	23.2 ± 2.6	22.5 ± 2.4	22.5 ± 2.2	21.7 ± 2.0
	CON	FWR	81.1 ± 10.2	84.4 ± 14.8	83.9 ± 12.1	78.6 ± 8.7	75.1 ± 9.2
		VR	84.4 ± 14.0	87.1 ± 14.2	78.3 ± 10.1	77.4 ± 8.5	76.8 ± 9.8
Peak Glut EMG (%MVC)	ECC	FWR	72.6 ± 7.0	78.3 ± 7.5	76.4 ± 7.2	74.6 ± 7.1	71.7 ± 6.9
		VR	79.1 ± 9.4	82.0 ± 9.5	76.7 ± 8.9	74.7 ± 5.5	71.7 ± 7.3
	CON	FWR	103.4 ± 10.8	111.3 ± 14.0	112.7 ± 12.5	103.3 ± 12.1	103.1 ± 9.6
		VR	115.9 ± 9.9	118.5 ± 10.7	110.8 ± 11.7	100.3 ± 7.9	99.7 ± 7.6

Acronyms: VL = vastus lateralis; VM = vastus medialis; Glut = gluteus maximum; EMG = electromyogram; MVC = maximum voluntary contraction; FWR = free-weight resistance; VR = variable resistance; ECC = eccentric; CON = concentric.



300x500mm (96 x 96 DPI)



250x200mm (96 x 96 DPI)