Title

THE INFLUENCE OF VARIABLE RESISTANCE LOADING ON SUBSEQUENT FREE WEIGHT MAXIMAL BACK SQUAT PERFORMANCE

ABSTRACT

The purpose of the study was to determine the potentiating effects of variable resistance (VR) exercise during a warm-up on subsequent free-weight resistance (FWR) maximal squat performance. In the first session, sixteen recreationally active men (age = 26.0±7.8 yr, height = 1.7±0.2 m, mass = 82.6±12.7 kg) were familiarized with the experimental protocols and tested for one-repetition maximum (1-RM) squat lift. The subjects then visited the laboratory on two further occasions under either control or experimental conditions. During these conditions, two sets of three repetitions of either FWR (control) or VR (experimental) squat lifts at 85% of 1-RM were performed; during the experimental condition 35% of the load was generated from band tension. After a 5-min rest, 1-RM, 3D knee joint kinematics, and vastus medialis, vastus lateralis, rectus femoris and semitendinosus electromyogram (EMG) signals were recorded simultaneously. No subject increased 1-RM following FWR, however 13 of 16 (81%) subjects increased 1-RM following VR (mean = 7.7%; $p<0.01$). Lower peak and mean eccentric (16-19%; $p<0.05$) and concentric (12-21%; $p<0.05$) knee angular velocities were observed during the 1-RM following VR when compared to FWR, however no differences in knee flexion angle (1.8°; $p>0.05$) or EMG amplitudes (mean = 5.9%; $p>0.05$) occurred. Preconditioning using VR significantly increased 1-RM without detectable changes in knee extensor muscle activity or knee flexion angle, although eccentric and concentric velocities were reduced. Thus, VR appears to potentiate the neuromuscular system to enhance subsequent maximal lifting performance. Athletes could thus utilize VR during warm-up routines to maximize squat performance.

KEY WORDS: elastic bands, post-activation potentiation, preconditioning, 1-RM, strength training.

INTRODUCTION

The free-weight back-squat exercise is one of the most commonly performed exercises in powerlifting, Olympic lifting, and recreational strength and conditioning routines, with several review articles reporting that the lift can elicit a post-activation potentiation (PAP) response and improve functional performance when used in a warm-up (17,26,30). Exercises designed to elicit PAP during training and/or before competition have been shown to influence neuromuscular characteristics, including peak force or strength (e.g. 1-RM), joint range of motion, velocity and muscle activity during the exercise (13,24). Two mechanisms theorized to explain the PAP phenomenon include (i) upregulating Ca^{2+} sensitivity of the myofilaments and phosphorylation of the myosin regulatory light chains (16,17,27), enhancing the excitation-contraction coupling process, and (ii) increasing descending neural drive via the recruitment and synchronization of faster motor units, or a decreased presynaptic inhibition at the spinal level (1,9,15,30). Regardless of the mechanism, PAP could enhance mechanical power above previous capacity when induced using maximal or near maximal contractions during a warm-up (8,9,14,15,24) and utilized during a subsequent MVC.

However, during a maximal (1-RM) back-squat exercise, the individual only operates maximally during a short period in the early ascending (concentric) phase, i.e. near the ‘sticking point’, and operates sub-maximally during the remaining concentric and eccentric phases. This phenomenon can be largely explained by the mechanics of the lift, where smaller internal and greater external moment arms are developed at the hip and knee during the eccentric phase of the lift. This results in a poor mechanical advantage and the force-length characteristics of lower limb muscles, which are sub-optimally long in the deep squat position (2,11). Therefore, the characteristics of the free-weight back squat lift may limit the potential for PAP development, thus limiting acute increases in strength observed during a warm-up.

Warm-up routines are specifically designed to precondition the neuromuscular system to enhance performance and reduce injury risk during high-intensity physical activity (6,32,34). In sports such as powerlifting and in strength and conditioning programs, such warm-up routines can act as a determining factor of the athlete's performance. A possible means of improving the back squat exercise during a warm-up to enhance subsequent maximal strength is the use of variable resistance using elastic bands. Elastic bands attached to a loaded barbell pull the bar down altering the mechanical loading and stresses placed through the musculoskeletal system during the lift, which may ultimately change movement patterns (29,33). The magnitude of this variable loading is dictated by the deformation of the bands, which is greater in the eccentric phase but reduces as the athlete lowers the bar, changing the loading characteristics of the lift (5,29) and affecting neuromuscular demand. Accordingly, the bands can be used to increase resistance at ranges of motion where the muscles can produce their greatest force, as well as unload the system where the muscles are weaker. Therefore, because load manipulation can allow a larger overall impulse to be produced, which is purportedly an important factor influencing PAP (2), it may be possible to further enhance strength performance.

Previous research has shown that the use of elastic bands in combination with free-weight (i.e. traditional) resistance results in performance improvements generating higher forces and power output compared to free-weight resistance alone (33) with increased movement velocity during the eccentric phase (29). Force production during the subsequent concentric phase is then likely enhanced via the combination of increased reflex amplitudes and a greater use of elastic energy stored in the muscle-tendon units during the eccentric phase (29), which ensures that the muscles work closer to their maximum through the lift. The increase in total muscle force production elicited by the use of bands should thus increase the magnitude of the PAP response, given that PAP tends to be augmented when a greater work is performed by the muscles (2,33). Such an improvement in force production during training could subsequently increase muscular adaptation and strength development (2,28). However, equivocal data exists on the influence of variable resistance exercise on the kinematics of squatting (10,18). Furthermore no research has examined the influence of elastic band use to vary the resistance during squat lifting on subsequent free-weight lifting performance. Strength coaches incorporating these elements in a warm-up routine may both enhance acute performance (i.e. increase 1-repetition maximum; 1-RM) and impose a greater mechanical stimulus (i.e. training load). As such, identifying the optimal warm-up routine to potentiate strength performance is of clear importance to strength coaches. Therefore, the purpose of the present study was to examine the influence of variable resistance exercise using elastic bands during a warm-up squat exercise on subsequent free-weight squat performance. It was hypothesized that the variation in resistance elicited by elastic band use during squatting in the warm-up would 1) enhance subsequent free-weight squat lift performance (measured as the 1-RM load) and 2) alter lifting mechanics of the 1-RM lift when compared to the traditional free-weight squat warm-up currently used by many athletes.

METHODS

Experimental Approach to the Problem

A randomized cross-over study was designed to compare 1-RM back squat performance following two warm-up conditions; either with VR (experimental) or FWR squat (control). The imposition of variable resistance using elastic bands may influence both the mechanical and neuromuscular profile of the squat lift and may result in a greater 1-RM lift being achieved when compared to a traditional free-weight (FWR) warm-up. The present study aimed to test these hypotheses using 3D motion analysis to record knee flexion and extension, and mean and peak concentric and eccentric knee angular velocities, while electromyography (EMG) was used to quantify knee extensor muscle activity during 1-RM trials following either a VR (experimental) or FWR squat (control) warm-up. The subjects visited the laboratory on three occasions at the same time of day, each separated by one week, and were dressed in Lycra shorts, t-shirts and athletic shoes for each session. They were initially familiarized with the testing protocol one week before data collection where the subjects' back squat 1-RMs were also determined. The subjects then visited the laboratory on two further occasions, once under control conditions using FWR and once under experimental conditions using VR with elastic bands, in a randomized, counterbalanced order. By examining variables other than 1-RM load we were able to determine whether other performance variables were influenced and whether they could explain any differences in 1-RM performance between conditions. Measuring knee flexion angle confirmed that a full repetition had been performed rather than a shallower squat under greater load. Eccentric and concentric knee velocities also provided information as to how the mechanics of the lift were influenced under potentially greater loading, while knee extensor EMG data afforded the ability to determine whether greater knee extensor activity was present and whether these changes could explain any increases in 1-RM.

Subjects

Sixteen physically active men (age mean = 26.0 ± 7.8 yr, range 18 to 44 yr, height = 1.7 ± 0.2 m; mass = 82.6 ± 12.7 kg) experienced in weight training (>3 yr) volunteered to participate in this study after giving written informed consent and completing a pre-test medical questionnaire. The subjects were healthy, had no recent illness or injury in the lower limbs or lower back, were instructed to maintain their eating and drinking habits throughout the study and avoided strenuous exercise and dietary stimulant use for 48 h prior to testing. Ethical approval was granted by the ethics committee at the University of Northampton in accordance with the Declaration of Helsinki.

Procedures

Overview

The subjects visited the laboratory on three occasions for familiarization, control and experimental sessions. During the control condition, the subjects performed a 5-min warm-up on a cycle ergometer (Monark 874E, Sweden) at 60 rpm with a 1-kg resistance load producing a power output of 60 W. Five minutes later, subjects performed two preconditioning sets (3 repetitions at 85% of the previously determined 1-RM) with 3 minutes of rest between sets to prepare for the 1-RM trial. After a further 5-min rest, the subjects attempted their previously recorded 1-RM, and after a successful lift the subjects attempted a lift with 5% greater load; any further successes resulted in an attempt with an additional 5% load (i.e. 10% total) to the nearest 1 kg. During the experimental condition, similar to previous studies (33), variable resistance from the bands was 35% of the total load. To ensure a similar total load during the squat exercise, half of the 35% load was taken off the bar during the preconditioning set (see below for additional information). Five minutes later, the subjects attempted their previously recorded 1-RM; each successful lift was followed by further attempts with 5% greater load. No subjects were able to lift more than 10% of their initial 1-RM.

One-repetition maximum (1-RM) assessment

All subjects were experienced at squatting (>3 yr) and completed 5-10 repetitions with appropriate and consistent technique during the familiarization session using a light resistance set at approximately 50% of 1-RM. A successful squat was considered as the posterior thigh being approximately parallel to the floor, flexing the knee joint more than 90º (4) before returning to a standing position. An experienced spotter was used throughout all testing procedures to ensure correct technique, safety during the lifts, and to provide uniform verbal encouragement to all subjects. A specific squat depth was not dictated to the subjects because an important aim of the research was to determine whether kinematics changed following the intervention. Squats were performed without the use of any supportive equipment (e.g. knee wraps, squats suits, weight lifting belts, etc.) and calibrated and certified Olympic standard weight lifting bar, plates, collars and rack (Eleiko, Sweden) were used throughout. In a method similar to that previously reported (4), gradual adjustments were made where the load was increased by 10-20% and the subjects then performed 3-5 repetitions, after a 2-min rest period the load was further increased by 10-20% and 2-3 repetitions performed. Two to four minutes later, the load was increased by 10% and subjects attempted to perform a 1-RM lift. The load was then increased by 5% with 2-4 min rest between lifts until the subjects failed to complete the squat; the previous successful lift was recorded as their 1-RM.

Intervention

In the FWR (control) condition, the load during the preconditioning sets was adjusted to 85% of the previously determined 1-RM and the subjects performed two 3-repetition back squat sets. However, elastic bands were used in conjunction with free weight resistance in the VR experimental condition to generate variable resistance during the preconditioning sets (see Figure 1). To ensure that a similar load of 85% 1-RM was performed in the VR condition, the mechanical properties of the elastic bands needed to be determined to enable 35% of the load to be generated from elastic resistance.

Figure 1 here

In the VR condition, it was vital to subtract half of the band's resistance from the total free-weight load to ensure that the elastic bands did not have higher average resistance compared to the FWR condition. Using methods previously reported (33), the subjects stood on a force platform (HUR, Finland) with 85% 1-RM loading to determine their combined load (kg); data were then directed to a personal computer running Research Line software (v.2.4). The bar was then unloaded and elastic bands were anchored to the floor with two custom-made weight stands, attached equidistant to the ends of the Olympic bar to ensure subject stability. The thicknesses and lengths of the elastic bands were adjusted so that the tension in them increased the force platform reading by 35% of the 85% load when the subjects were standing but were slack in a full squatting position, and thus contributed no loading. Therefore, due to the linear force-length properties of the elastic bands, the average loading 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 in the VR condition. Half of the 35 kg load (i.e. 17.5 kg) would be removed from the bar leaving 82.5 kg on the bar, combined with the 35 kg from the bands giving a total load of 117.5 kg in the standing position. As the subject squats, tension is reduced in the bands, thus 35 kg of load has been removed, resulting in only the 82.5 kg load from the bar remaining. Therefore, a range of 35 kg (35%) is achieved through variable loading using the elastic resistance from the bands, while maintaining an average loading of 100 kg throughout the lift, identical to the FWR condition.

To determine the effect of free-weight (FWR) and variable resistance (VR) preconditioning sets on maximal squat performance, the subjects attempted a 1-RM lift at their previously determined maximal load after a passive (seated) 5 min rest. Similar to the 1-RM trials performed in the familiarization session, subjects then attempted lifts with successive 5% increases of their 1-RM load with 5 min rest until they reached their maximum lift; no subjects were able to lift more than 10% of their initial 1-RM.

Muscle Activity

Skin-mounted bipolar double-differential active electrodes (model MP-2A, Linton, Norfolk, UK) constantly monitored the EMG activity of vastus medialis (VM), vastus lateralis (VL), rectus femoris (RF) and semitendinosus (ST). EMG signals were amplified (gain = 300, input impedance = 10 GΩ, common mode rejection ratio ≥100 dB at 65 Hz) and directed to a high-level transducer (model HLT100C, Biopac) before being converted from an analog to digital signal at a 2,000-Hz sampling rate (model MP150 Data Acquisition, Biopac). The signals were then directed to a personal computer running AcqKnowledge software (version 4.1), filtered using a 20-500 Hz band-pass filter, and converted to root-mean-squared (RMS) EMG with a 250-ms sample window. The RMS EMG data were then normalized as a percentage of the peak amplitude recorded during a maximal countermovement vertical jump; VL, VM, and RF data were then averaged to represent quadriceps femoris (QF) EMG. The normalized EMG amplitudes (%MVC) were used as a measure of neuromuscular activity during the squat exercises with peak and mean EMG activity recorded during the concentric and eccentric phases.

Motion analysis

Real-time motion analysis was performed using four ProReflex cameras (Qualisys, Sweden) operating Track Manager 3D (v.2.0) software. The position of three spherical infrared reflective markers (20 mm) placed over the greater trochanter, lateral femoral epicondyle and lateral malleolus were recorded in order to determine knee flexion range of motion (ROM) and both mean and peak eccentric and concentric knee angular velocities during the 1-RM trials. Similar to previous studies (20,21), raw coordinate data were sampled at 100 Hz and smoothed using a 100-ms moving average before joint angle and velocities were calculated using Track Manager 3D (v.2.0) software. The positions of the markers were initially recorded with the subjects in the anatomical position to enable knee angle data to be corrected (180° full extension) before knee flexion ROM and peak and mean eccentric and concentric knee velocity data were calculated.

Statistical Analyses

All data were analyzed using SPSS statistical software (version 17.0). Parametric assumptions of normal distribution were met. To determine the influence of the warm-up conditions on subsequent 1-RM performance, separate repeated measures MANOVA's were used to determine if there was a significant difference in 1) peak and average eccentric and concentric velocities and 2) peak and average eccentric and concentric EMG activity during initial 1-RM trials (same load; 136.1 ± 5.6 kg) following control (FWR) and experimental (VR) conditions. Paired t-tests were then used to locate significant differences in squatting knee angle between conditions.

As some subjects were able to increase their 1-RM, further analyses were conducted on the best 1-RM performance between conditions (greatest load). Again, separate repeated measures MANOVA's were used to determine if there was a significant difference in 1) peak and average eccentric and concentric velocities and 2) peak and average eccentric and concentric EMG activity during the greatest 1-RM performance following FWR and VR conditions. Paired t-tests were then used to locate significant differences in squatting knee angle and 1-RM load between conditions. Significance was accepted at $p < 0.05$ for all tests.

Power analysis

To ensure an adequate participant population to reach statistical power (set at 0.8) was recruited for the study, effect sizes were initially calculated from related research (3) for velocity (3.5) and power (2.2); sample sizes were calculated at 6 and 10 participants, respectively. Therefore, to ensure an adequate population to reach statistical power (i.e. 10 participants), and considering the possibility of participant withdrawal, 16 participants were recruited to participate in the present study.

Reliability

Reliability for peak and average concentric and eccentric EMG, peak and average concentric and eccentric knee angular velocity, and knee flexion angle data were determined during two warm-up sets from the 2nd repetition of each set during the FWR condition warm-up. No significant difference was detected in any measure between repetitions ($p > 0.05$). Intraclass correlation coefficients (ICC) for EMG data ranged from 0.93 to 0.98, 0.91 to 0.95, 0.61 to 0.97, 0.97 to 0.99, and 0.94 to 0.96 for RF, VL, VM, ST and QF, respectively. ICCs for knee angular velocities and knee flexion angle ranged from 0.88 to 0.96 and were 0.97 respectively. Coefficients of variation (expressed as a percentage of the mean) were also calculated for EMG data and ranged from 9 to 13.7%, 6.7 to 12%, 5.2 to 7.7%, 11.4 to 20.2%, and 5.4 to 10% for RF, VL, VM, ST and QF, respectively. Coefficients of variation for knee angular velocities and knee flexion angle ranged from 6.1 to 8.2% and were 1.8%, respectively.

RESULTS

The influence of FWR (control) and VR (experimental) warm-up sets on subsequent free-weight 1-RM kinematics and neuromuscular activity of the knee joint were examined initially at the same 1-RM load (136.1 ± 5.6 kg). Five minutes after the warm-up, all subjects successfully lifted their previously determined 1-RM indicating that neither warm-up induced fatigue. No differences in peak or mean EMG ($p > 0.05$), or peak or mean knee angular velocities ($p > 0.05$), were found during the eccentric or concentric phases of the lift. Despite similar movement kinematics being adopted in the eccentric and concentric phases under the same load, a deeper knee flexion angle (3.4°; $p < 0.05$) was achieved following the VR preconditioning compared to the FWR preconditioning (see Figure 2). Thus, the subjects squatted to a greater depth following the VR warm-up when measured under the same load.

Figure 2 here

Following the first 1-RM trial (136.1 ± 5.6 kg), the subjects then attempted a 5% and, if successful, a 10% increase in loading to determine any potentiating effects of the warm-up conditions. No subject was able to successfully lift a greater load following the FWR warm-up condition. However, following the VR condition, 13 of 16 subjects (81%) were able to successfully increase their 1-RM load by 5-10% (1-RM = 146.6 ± 5.7 kg). The significantly greater 1-RM (see Figure 3) following VR (7.7%; $p < 0.01$) is indicative of a potentiating effect on squat performance.

Figure 3 here

Significantly slower peak (17.4°·s^{-1}; $p < 0.05$) and mean (7.4°·s^{-1}; $p < 0.05$) eccentric knee angular velocities were found when measured during their maximum load following VR than FWR, however no changes in peak or mean eccentric EMG amplitudes ($p > 0.05$) were detected (see Table 1). Similarly, significantly slower peak (35.8°·s^{-1}; $p < 0.05$) and mean knee angular velocities (10.8°·s^{-1}; $p < 0.05$) were found during the concentric phase in the VR condition, although again no difference in EMG was detected. Despite the greater load and slower movement, no difference in peak knee flexion angle (1.8°; $p > 0.05$) was found, indicating that a similar squat depth was achieved and that a full repetition was performed.

Table 1 here

DISCUSSION

The primary aim of the present study was to compare the influence of variable resistance (VR) and free-weight resistance (FWR) warm-ups on: 1) subsequent free-weight 1-RM performance (measured as the 1-RM load) and 2) lifting mechanics and neuromuscular activity during the 1-RM. During the initial 1-RM attempt following both interventions, all subjects were able to lift their previously determined 1-RM with no differences found in eccentric or concentric velocities or EMG activity. However, a significantly greater knee flexion angle was achieved following VR warm-up, indicating that the subjects volitionally squatted to a greater depth. Despite the greater squat depth placing the subjects at further mechanical disadvantage due to internal and external moment arms and force-length properties of skeletal muscle (2,11), concentric velocities were similar to the FWR condition. The greater squat depth while maintaining velocity is indicative of the subjects more easily tolerating the same load while performing greater muscular work without limiting or compromising the mechanics of the lift.

While the choice to squat to a greater squat depth without reducing movement velocity provided some evidence that the subjects more easily tolerated the load. The primary aim of this study was to determine whether a greater 1-RM load could be lifted following a VR warm-up. The main finding of the present study was that, when compared to a standard warm-up of free-weight squats, subsequent squat lift 1-RM was greater when a variable resistance was performed using elastic bands in the warm-up; therefore we can accept the first experimental hypothesis that 1-RM would be increased. VR training is typically used to reduce the effective load near the ‘sticking point’ experienced early in the concentric phase of the squat lift, but then allows for greater loading later in the concentric phase when the joints are more extended, the internal moment arms are greater and optimal muscle lengths are achieved, and the load would therefore be easier to lift (2). According to Anderson et al. (2), a less acute sticking point may have allowed for greater muscle fibre recruitment and stimulation during the eccentric phase that may bring greater neuromuscular adaptations and type IIx muscle fiber recruitment. Thus, the use of VR changes the loading pattern during the squat to allow for loading to be closer to the maximal capacity of the lower limb musculature as the capacity changes throughout the lift. The ability for muscles to operate closer to their maximum through a greater proportion of the lift may have allowed for an enhanced PAP effect and an increased 1-RM capacity. Some authors have suggested that performance may be enhanced after chronic VR training due to improvements in muscular strength and power (2,5,18,28,29,33), however no study had previously examined the effects of VR as a preconditioning exercise as part of a warm-up on a subsequent free-weight 1-RM squat performance. Accordingly, these are the first data confirming that an acute increase in free-weight 1-RM squat performance can be elicited by VR preconditioning, which is clearly important for coaches and athletes where maximal strength development is crucial for performance.

The duration of PAP is suggested to be intensity dependent, with higher intensity contractions resulting in greater enhancement of motor unit recruitment and/or magnifying the phosphorylation of regulatory light chains (27). These effects are typically notable within minutes of the preconditioning activity being performed (23). However, several studies have indicated that PAP is maximal 4-12 minutes after a preconditioning activity when measured during voluntary contractions (19,22,23). Therefore, increased phosphorylation of regulatory light chains is an unlikely mechanism influencing PAP during the squat exercise tested presently. Instead, changes in the magnitude of activation of the muscles, perhaps through changes in spinal excitability or influences from afferent projections (15,31), are more likely factors. In the present study, a clear increase in 1-RM was noted 5 min after the preconditioning activity, which is in line with previous findings and is within the timeframe normally associated with neural, but not muscular changes (19,22,23). Despite this, no change in knee extensor EMG amplitude was detected. The lack of change in quadriceps EMG is consistent with previous studies where no change in EMG was found despite an increase in loading (7). Ebben and Jensen (10) compared free-weight squats to variable resistance of (10% supplied by elastic bands) and reported no difference in EMG activity from the quadriceps and hamstrings during these techniques. One potential explanation for this finding is that muscles other than the quadriceps, including the hip extensors, were activated differently after the VR squats. In fact, Flanagan and Salem (12) examined hip and knee extensor contributions during the squat lift exercise and reported that increases in load required greater mechanical efforts from the hip than the knee extensors. EMG activity of the hip extensors was not examined in the present study and joint torque measurements were not obtained. Although the semitendinosus contributes to hip extension, it has a dual role as a knee flexor and no change in its EMG activity was found in the present study, although trends for greater EMG in the semitendinosus were apparent. Thus, this hypothesis needs to be more explicitly examined in future studies.

An alternative possibility is that the improvement resulted from a modification in lifting technique. However, a significant difference in peak knee flexion angle was not observed after VR when compared to FWR, despite subjects increasing their load after the VR condition. The most likely outcome was that VR resulted in an enhanced neuromuscular output that enabled a greater force production and thus an increased 1-RM (5, 33). Nonetheless, although 1-RM increases occurred without a noticeable technique change (i.e. squat depth), peak and mean knee angular velocities during both the eccentric and concentric phases of squat exercise were reduced. Therefore, given squat depth was unchanged while knee velocities were reduced, we can partially accept the second hypothesis that lifting mechanics would be altered. Previous research examining lifting mechanics during VR have reported increased eccentric velocity (5,29), which appears to contradict the findings in the present study. However, Baker and Newton (5) measured velocity during the VR condition rather than after during free-weight exercise, using chains rather than bands, and during a bench press rather than back squat exercise. Therefore substantial differences in methodology likely explain these differences. Furthermore, Stevenson et al. (29) examined knee velocities during VR squat exercise rather than in a subsequent free-weight effort. During the eccentric phase the musculature provides mechanical force to oppose gravity in order to decelerate, and ultimately halt the downward motion of, the body and bar (i.e. the load). Thus, an impulse is required to change the momentum of the load. The reduction in eccentric velocity might have resulted from the need to minimize the load's momentum during the descent so that the impulse provided by the subjects was sufficient to decelerate, and then re-accelerate, it. Similarly, the greater loading might have limited the maximal concentric velocity unless a substantial change in the muscles' force-velocity characteristics (25) occurred after the VR repetitions. While the reduction in eccentric and concentric knee velocities was likely a result of the greater loading (25), the subjects were still able to squat to the same knee angle and complete the exercise. This clearly demonstrates that a full repetition was performed, and that 1-RM, mechanical output and force generating capacity were enhanced, which is of great importance to strength and conditioning coaches whose primary aim is to maximize strength potential of their athletes.

In summary, performing free-weight resistance back squat exercise in combination with elastic bands enhances subsequent free-weight squat lift performance without any noticeable change in squat depth, although movement velocities were reduced. As no change in knee extensor EMG was found, the mechanisms underpinning these improvements in performance remain unclear and further research is needed; specifically, the examination of hip extensor muscle activity appears essential. Although a significant increase in 1-RM was achieved following VR, 3 subjects did not improve their 1-RM performance. To ensure these subjects' data did not influence the statistical findings for EMG, velocity and knee flexion angle, subsequent analyses were undertaken without these subjects included. Identical statistical outcomes were found compared with the original analyses; therefore inclusion of non-responders in the analysis did not influence the study's conclusions. The positive effects observed presently were recorded in recreationally active male subjects during a complex multi-joint strength-based skill, and further research is required in elite populations (i.e.

powerlifters), across sexes, and in other muscle groups in single and multi-joint exercises to fully determine the influence of variable resistance on strength performance.

PRACTICAL APPLICATIONS

Warm-up sets to precondition the neuromuscular system are commonly used with the aim of enhancing muscular strength-based performance. In the present study, the use of variable resistance (VR) during warm-up significantly increased subsequent free-weight 1-RM performance without noticeably affecting movement technique compared to a traditional warm-up. These results could be beneficial to strength trained athletes (i.e. powerlifters, Olympic weightlifters) as variable resistance incorporated into warm-up routines before training or competition is likely to potentiate the neuromuscular system and facilitate greater strength capacity. Furthermore, the use of variable resistance provides the strength and conditioning practitioner greater flexibility in designing warm-up routines and exercise variety. The key message for strength and conditioning coaches is that the use of VR repetitions (~35% of load supplied from elastic bands) can be used as a training modality to improve performance in maximal squat lifts, and thus its use in strength-based athletes should be encouraged. Practically, this might also influence longer-term strength gains or hypertrophic adaptations by allowing greater loads to be lifted or for more repetitions to be completed at specific loads. Additionally, VR sets performed during warm-up might be expected to improve performance in single-lift sports, such as powerlifting and Olympic weightlifting, and this should be explicitly tested in athletes. Importantly, VR methodologies using elastic bands are relatively inexpensive and easily implemented, and thus may be utilized by most athletes.

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FIGURE LEGENDS

Figure 1. EMG electrode and infrared reflective motion analysis marker placement during the back squat exercise. Infrared reflective markers were placed over the lateral malleolus, femoral epicondyle and greater trochanter of the right lower limb to enable knee kinematics to be recorded, while EMG electrodes were positioned over the muscle bellies of the rectus femoris, vastus lateralis and medialis, and semitendinosus enabled muscle activity to be recorded. Elastic bands attached to the barbell provided an average of 35% of the total loading during the squat exercise.

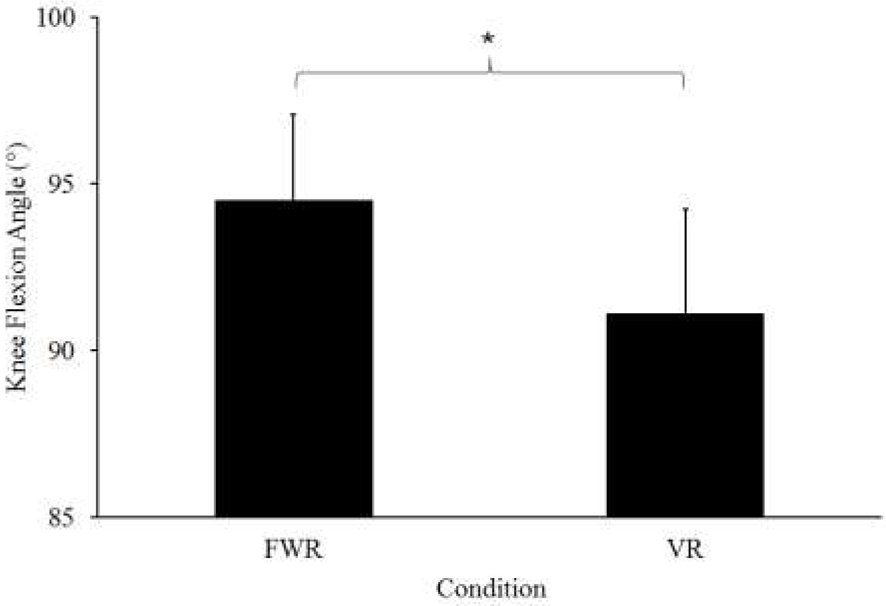


Figure 2. Mean knee flexion angle achieved during initial 1-RM free-weight back squat exercise at the same load (136.1 ± 5.6 kg) following a free-weight (FWR) or variable resistance (VR) warm-up set. *Significantly (3.4°; $p < 0.05$) greater knee flexion angle was achieved following VR compared to FWR.

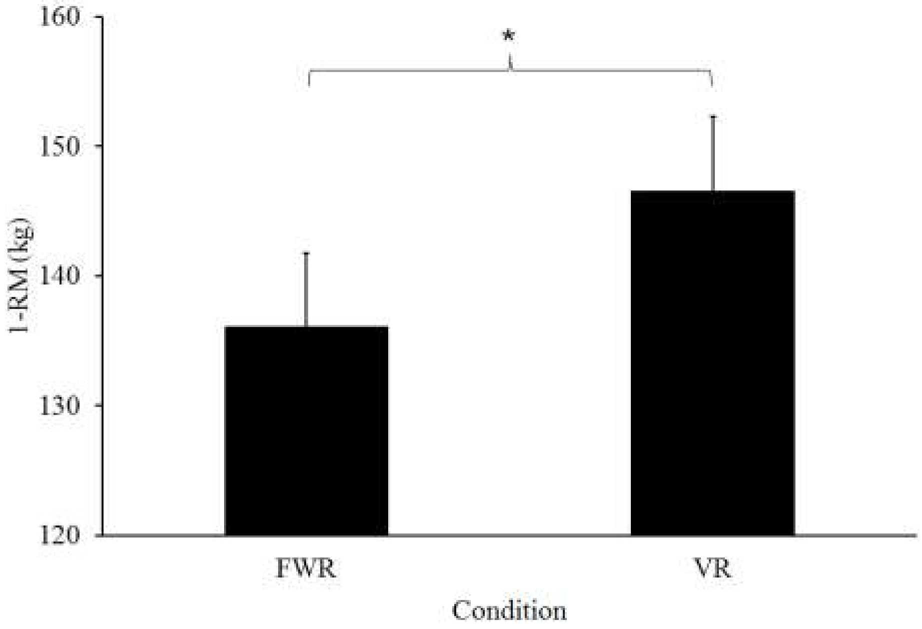
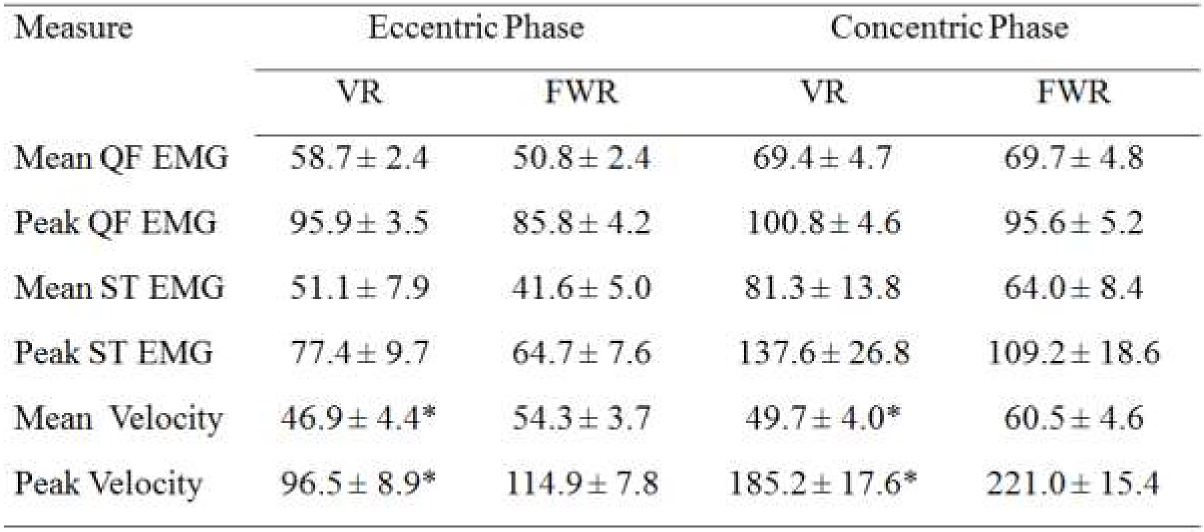


Figure 3. Mean 1-RM load achieved during a 1-RM free-weight back squat exercise following a free-weight (FWR) or variable resistance (VR) warm-up set. *Significantly (7.7%; $p < 0.01$) greater load was achieved following VR compared to FWR.

Table 1. Mean and peak quadriceps femoris (QF) and semitendinosus (ST) electromyogram amplitude (%MVC) and knee angular velocities (°·s^{-1}) measured during greatest 1-RM free-weight back squat exercise achieved following a free-weight (FWR) or variable resistance (VR) warm-up set (*$p < 0.05$ compared to FWR condition).



Measure	Eccentric Phase		Concentric Phase	
	VR	FWR	VR	FWR
Mean QF EMG	58.7 ± 2.4	50.8 ± 2.4	69.4 ± 4.7	69.7 ± 4.8
Peak QF EMG	95.9 ± 3.5	85.8 ± 4.2	100.8 ± 4.6	95.6 ± 5.2
Mean ST EMG	51.1 ± 7.9	41.6 ± 5.0	81.3 ± 13.8	64.0 ± 8.4
Peak ST EMG	77.4 ± 9.7	64.7 ± 7.6	137.6 ± 26.8	109.2 ± 18.6
Mean Velocity	46.9 ± 4.4*	54.3 ± 3.7	49.7 ± 4.0*	60.5 ± 4.6
Peak Velocity	96.5 ± 8.9*	114.9 ± 7.8	185.2 ± 17.6*	221.0 ± 15.4