ACUTE EFFECTS OF ELASTIC BANDS DURING THE FREE-WEIGHT BARBELL BACK SQUAT EXERCISE ON VELOCITY, POWER, AND FORCE PRODUCTION

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ABSTRACT

Stevenson, MW, Warpeha, JM, Dietz, CC, Giveans, RM, and Erdman, AG. Acute effects of elastic bands during the free-weight barbell back squat exercise on velocity, power, and force production. *J Strength Cond Res* 24(11): 2944–2954, 2010—The use of elastic bands in resistance training has been reported to be effective in increasing performance-related parameters such as power, rate of force development (RFD), and velocity. The purpose of this study was to assess the following measures during the free-weight back squat exercise with and without elastic bands: peak and mean velocity in the eccentric and concentric phases (PV-E, PV-C, MV-E, MV-C), peak force (PF), peak power in the concentric phase, and RFD immediately before and after the zero-velocity point and in the concentric phase (RFD_C). Twenty trained male volunteers (age = 26.0 ± 4.4 years) performed 3 sets of 3 repetitions of squats (at 55% one repetition maximum [1RM]) on 2 separate days: 1 day without bands and the other with bands in a randomized order. The added band force equaled 20% of the subjects' 55% 1RM. Two independent force platforms collected ground reaction force data, and a 9-camera motion capture system was used for displacement measurements. The results showed that PV-E and RFD_C were significantly ($p < 0.05$) greater with the use of bands, whereas PV-C and MV-C were greater without bands. There were no differences in any other variables. These results indicate that there may be benefits to performing squats with elastic bands in terms of RFD. Practitioners concerned with improving RFD may want to consider incorporating this easily implemented training variation.

KEY WORDS rate of force development, variable resistance training, stretch-shortening cycle

INTRODUCTION

Force development is critical to the performance of virtually all sports and plays an integral role in key parameters such as velocity and power development (24). In particular, the generation of maximal muscular force (maximal strength) has been given considerable attention over the years in both the training and testing of athletes. Although this key component is clearly linked to athletic performance, the rate of force development (RFD; an index of explosive strength), power output, and speed development have been suggested by some to be equally, or more, important in predicting success in athletic performance (12,19,29,32). As a result, much effort has been spent by sports scientists and coaches in search of the optimal methods by which to train and improve power production and force development, particularly in the back squat exercise (2,9,10,16,25,34–36,42,43,45).

Elastic bands offer variable resistance throughout a range of motion (17), and their incorporation with exercise movements has long been used for rehabilitation purposes. More recently, however, elastic bands have found a niche in many strength programs because of the purported performance benefits (34,42). Elastic bands for rehabilitation are characterized by portability, light resistance, and versatility. In contrast, the elastic bands used in a strength training environment are thicker and have been used as a form of variable resistance training (VRT), which accommodates the strength curve of extension-type exercises. Additionally, elastic bands have been used in strength training as a means to create an overspeed eccentric phase, which has been shown to enhance the effects of the stretch-shortening cycle (SSC) (36). The SSC is a component of virtually all dynamic movements that involve a lengthening (eccentric) and shortening (concentric) of the muscle–tendon unit (i.e., series elastic component) during the reversal phase of the movement. Although the SSC and the associated mechanisms of greater force production have been described at length elsewhere (14,18,26,27,31,33,43,44), it can briefly be said that the increased concentric force produced by the SSC phenomenon is the result of

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a combination of neural reflexes and the ability to use stored elastic energy in the muscle–tendon unit. A major training benefit incurred by enhancing the SSC phenomenon is increased power production (28), which is linked to RFD and velocity of movement. The RFD on both sides of, and in close proximity to, the zero-velocity point (which occurs within the reversal [coupling] phase of the exercise) is of particular interest because of the implications of the SSC.

Many practitioners advocate the use of elastic bands in their strength programs. Although there is anecdotal evidence that supports the use of elastic bands over traditional resistance training (38–40), there is a paucity of research on the topic. The few studies that have sought to quantify the benefits of band training during the back squat, as they relate to force and power production, have yielded conflicting results and have each used different designs and methodologies (2,11,16,34,42). Limitations of these studies have been the metrics assessed, the instrumentation used to collect data, small sample sizes, and inconsistent protocols as they relate to type of exercise, load and apparatus used, and technique. For example, squatting-type movements performed on Smith machines and leg press machines constrain the movement to a single plane and do not represent the multidimensional movement of most sport activities (10). In addition, squat depth is rarely quantified, and differences in squat depth can create varying results. From the current literature, variations in range of motion, apparatus, and measurement techniques make it difficult to form an overall conclusion about elastic band training. Lastly, studies that involve multiple testing days rarely implement strategies to determine the subjects' general state on each day in terms of fatigue level, muscle soreness, neuromuscular status, etc.

The current study incorporated the free-weight barbell version of the squat exercise because it is frequently used as a fundamental training exercise across many sports. The equipment and instrumentation used for data collection ensured that extrapolation, estimation, and assumption of such critical components as force and velocity were kept to a minimum. The inclusion of the free-weight exercise and the instrumentation and methodology used for data collection are significant enhancements to this study. The use of 2 force plates and a 9-camera motion capture system allowed for independent force and displacement data as recommended by Hori et al. (21), and the free-weight back squat is an exercise that allows for free movement in space, which is reflective of most sport activities. The purpose of this study was to assess the following variables during the free-weight back squat exercise with and without the application of elastic bands: peak velocity in the eccentric and concentric phases (PV-E, PV-C), mean velocity in the eccentric and concentric phase (MV-E, MV-C), peak force (PF), peak power in the concentric phase (PP-C), and RFD values immediately before the zero-velocity point at the bottom of the movement (RFD_A), immediately after the zero-velocity point (RFD_B), and in the concentric phase (RFD_C).

METHODS

Experimental Approach to the Problem

This study was designed to determine whether a greater eccentric force that is applied with elastic bands translates into a faster and more powerful concentric phase in the barbell back squat exercise when compared to a condition in which no bands are used. It was hypothesized that bar velocity in the eccentric phase with bands would be greater than the nonband condition because of the increased acceleration (via increased force) provided by the elastic bands. It was further hypothesized that this increased velocity would translate into a faster and more forceful concentric phase because of the SSC phenomenon and yield increased values for all variables observed in this study: velocity (PV-E, PV-C, MV-E, MV-C), power (PP-C), force (PF), and RFD (RFD_A, RFD_B, RFD_C).

Subjects came to the laboratory on 3 separate days. The first day (day 1) involved the screening and consent process, the collection of biometric data, and the estimation of each subject's 1 repetition maximum (1RM). Day 1 was performed at least 3 days before the first experimental condition (day 2). The following week, on days 2 and 3 (separated by 72 hours in a Monday–Thursday or Tuesday–Friday testing format), each subject performed 3 sets of 3 repetitions of the back squat with 5 minutes of rest between sets. The resistance on the bar was chosen to be 55% of the predicted 1RM. This percentage was chosen because it falls near the average percentage that has been reported in the literature to be most effective in eliciting maximum power production (5,9,24,36,45). For each condition, the subject performed the squat with the same constant weight on the bar (55% 1RM) but with additional force (20% of the 55% 1RM at standing position) provided by bands on 1 day. The 20% additional force from the bands was chosen because it fell within the range of values used in previous studies and represented a practical load for the bands to exert (11,16,42). The 2 conditions, no bands (NB) and with bands (WB), were randomized so that half of the subjects performed squats with bands on the first experimental day and without bands on the second experimental day, and vice versa for the other half of the subjects.

Subjects

Twenty-two healthy men (26.0 ± 4.4 years) who were experienced in weight training (mean experience = 10.4 ± 4.7 years), including the back squat exercise, were recruited for the study. Inclusion criteria were (a) at least 1 year of resistance training experience, (b) self-reported familiarity with performing the free-weight barbell back squat exercise, (c) male, and (d) 18–35 years of age. Exclusion criteria included (a) high blood pressure (resting systolic > 139 mm Hg or resting diastolic > 89 mm Hg) and (b) prior or current musculoskeletal injury that could be made worse by performing the back squat exercise (e.g., knee, ankle, hip, shoulder, low back). Two subjects did not complete the study because of injury; 1 subject sustained a rib injury during the preliminary testing phase, and the other injured his ankle in an unrelated activity. The biometric data and characteristics of the 20 subjects who completed the study are presented in Table 1. All subjects were informed of the experimental risks and signed an informed consent document before the investigation. The investigation was approved by the Institutional Review Board for the use of human subjects at the University of Minnesota.

Procedures

Preliminary Testing. After completing the screening and informed consent process, subjects were measured for biometric data. Height was measured to the nearest 0.1 cm with a wall-mounted stadiometer (Seca, Hamburg, Germany), and weight was recorded to the nearest 0.1 kg with a certified digital scale (Tanita BW-800A, Arlington Heights, IL, USA). Body composition was assessed via densitometry using the hydrostatic method. After the collection of biometric data, each subject's 1RM was determined. The subject warmed up for 5 minutes on a stationary, upright bicycle at a workload of approximately 80 W. After the general bike warm-up, the subject performed a specific warm-up that consisted of several sets that followed a trend of increasing load and decreasing repetitions. All squats performed in this study had trained spotters present and used a calibrated and certified competition power lifting set (bar, plates, and collars) in kilograms (Ivanko, Los Angeles, CA, USA). Squats were performed without the use of any type of supportive equipment (e.g., squat suits, knee wraps). Maximal back squat strength was estimated via a 4–6RM protocol in which the subjects gradually worked up to a weight that induced failure after 4, 5, or 6 complete unassisted repetitions. During all squats, subjects were instructed to descend to at least the point at which the tops of their thighs were parallel to the floor. Once the maximum weight for a 4, 5, or 6RM was established, maximum squat strength (1RM) was estimated using the %1RM–repetition relationship (4).

Testing Procedure. The experimental conditions occurred on 2 days: 1 in which squats were performed with bands (WB) and the other with no bands (NB). These experimental conditions were randomized and performed the week after the preliminary testing. All subjects chose either a Monday–Thursday or Tuesday–Friday testing format to ensure consistent and adequate recovery times. Subjects were instructed to refrain from heavy exercise the day before a testing trial. Subjects arrived at the laboratory each testing day and were weighed and performed the general warm-up on the bike as previously described in the preliminary testing section. After the general warm-up, subjects performed vertical jump (VJ) and hand dynamometry (HD) tests to ensure that their overall neuromuscular status was consistent (statistically similar, $p \geq 0.05$) between the 2 testing days. Three maximal jumps were performed and recorded to the nearest 0.5 in. (1.27 cm) using a Vertec^{TM} VJ testing device (Sports Imports Inc., Columbus, OH, USA), and the highest score was recorded. For the HD test, maximal isometric grip strength was measured with a handheld dynamometer (Baseline, Irvington, NY, USA) 3 times in each hand in an alternating format and recorded to the nearest 1.0 kg. The highest score for each hand was recorded and summed to yield the final recorded value. Subjects were also weighed at the beginning of each experimental day to ensure that body weight was not significantly different between the 2 conditions.

Table 1. Mean ± *SD* values for age, body mass, height, % body fat, and years of training experience for subjects ($n = 20$).

Characteristic	M ± *SD*
Age (y)	26.0 ± 4.4
Body mass (kg)	87.8 ± 12.6
Height (cm)	180.4 ± 9.1
Body fat (%)	14.4 ± 6.0
Experience (y)	10.4 ± 4.7

After the general warm-up and neuromuscular testing, subjects were fitted with 4 hemispherical reflective markers that would be used to quantify squat depth using a 3D motion capture system. Two markers were taped on each side of the body in a symmetrical fashion at the knee (the marker was placed laterally at the level of the joint space between the femur and tibia) and hip (greater trochanter). For the purpose of measuring bar velocity, a marker was also placed on the center of the barbell. All subjects performed the squats wearing spandex shorts to minimize excessive marker movement at the hip, and thigh angle was defined as the angle created between the vertical plane and the knee–hip vector, as shown in Figure 1. Markers were always placed by the same individual to ensure consistency of placement. Once the markers were securely placed in the correct positions the subject began their squat-specific warm-up. This warm-up followed a similar procedure as the one used for preliminary strength testing except the final weight was 55% 1RM as opposed to 85–90% 1RM. The warm-up protocol was matched exactly between the first and second experimental days. Next, the bar was loaded to the corresponding 55% 1RM resistance (rounded to the nearest 2.5 kg to accommodate the smallest weight plate denomination). During the NB condition, the bar was simply loaded to the 55% 1RM weight. During the WB condition, the appropriate band tension was determined and applied. The "mini" bands (Jump Stretch Inc., Youngstown, OH, USA) were attached on each side of the bar (in a symmetrical and equidistant fashion) and anchored with loading pins threaded through 50-kg plates that were laid flat. The loading pins were situated so that the bands were vertical during the squats. The upper end of each band was looped around the

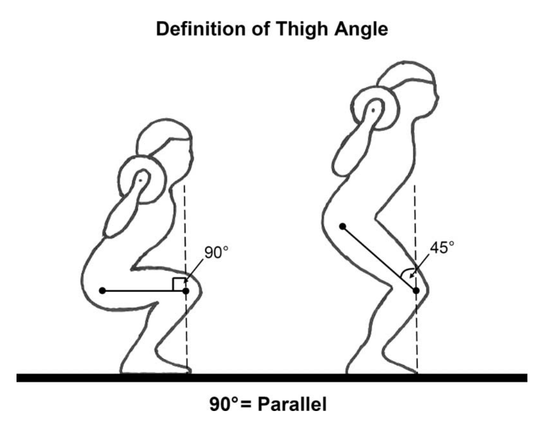


Figure 1. A drawing representing the definition of the thigh angle used throughout the study. The angle is defined by the vector created by the knee and hip markers and the vertical plane.

bar (Figure 2). The number of times the band was looped around the bar was determined by how much tension was required for the individual. In the WB condition, the bands exerted maximal tension (20% of the 55% 1RM) in the fully erect starting (and finishing) position and zero tension (bands slack) in the bottom position to equalize the loads at the zero-velocity point of the reversal phase for each experimental condition. This method was used to equalize the weight in both conditions to accurately analyze the SSC and its effects. Looping the bands around the bar was the most effective method by which to achieve the 20% target. All subjects were within 1% of the 20% target (overall mean ± *SD*; 20.10 ± 0.46%). Determining the number of loops was a trial-and-error process that involved having the subject initially stand on the force plate with just the empty bar and then repeating the process 2 or 3 more times with varying numbers of loops. The band tension was simply calculated by taking the differences in recorded weights. The goals were to ensure that (a) the bands added the prescribed force in the upright position (starting and finishing points), and (b) the bands were slack at the bottom of the squat (transition from the eccentric to concentric phase) so as to equalize the loads at this position between experimental conditions. It should be noted that in 4 subjects, the band tension was slightly greater than zero at the bottom; this was because of either a greater tension requirement for strong subjects or very tall subjects with a greater range of motion.

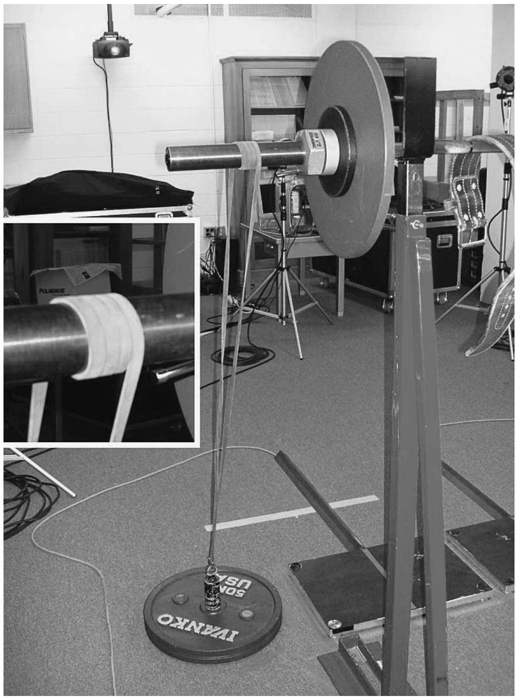


Figure 2. Picture showing the physical setup, including the methods for creating band tension and the anchoring system for the elastic bands.

Once the warm-up was completed (and band tension calculated for the WB condition), subjects were instructed to perform 3 sets of 3 repetitions of the squat with 5 minutes of rest between sets to allow for recovery of the phosphagen adenosine triphosphate (ATP) energy system (4). Sets of 3 repetitions were chosen because of the observation that power output decreases significantly after 3 repetitions in power exercises (6). Once given the signal, the subject placed the bar on his back and took 1 step backward and assumed a symmetrical stance (self-selected stance width) on the force plates. Each subject then began the set of 3 repetitions at his or herr own discretion. The 2 major instructions given to the subjects regarding the performance of the squat were to (a) descend to a depth at least equal to the tops of thighs being parallel to the floor and (b) descend and ascend as fast as possible (i.e., complete each repetition as quickly as possible).

Data Collection and Analysis

Biomechanical data were collected using a 9-camera motion capture system (SMART-e, BTS Bioengineering SPA, Milan, Italy) and 2 portable force platforms (Kistler, 9286AA, Winterthur, Switzerland), which provided a separate yet time-synchronized measurement of both displacement and force data. The cameras and force plates were controlled using the SMART software package (includes SMARTcapture, SMARTtracker, SMARTanalyzer, and SMARTviewer, version 1.10.346.0, BTS Bioengineering SPA). The 2 force platforms measured vertical ground reaction forces (GRFs) for each foot, which were later added to yield a net force in the vertical direction. Both force plates were zeroed before each set, and the sampling frequency was set at 960 Hz. Vertical displacement data were acquired via the infrared camera system and a reflective hemispherical marker taped to the center of the barbell. The sampling frequency of the cameras was 60 Hz. The camera and force plate system were calibrated before each of the testing days.

SMARTcapture was used for recording the data; the signals were collected via analog hubs and an Analog-to-Digital Converter (ADC) Peripheral Component Interconnect (PCI) card, both part of the SMART system. The displacement and force data were filtered in SMARTanalyzer using a moving average rectangular smoothing window with widths of 5 frames and 7 frames, respectively. Data were then analyzed to determine the dependent variables using SMARTanalyzer and MATLAB (Ver. R2006b, The Mathworks, Inc., 2006). All dependent variable values were calculated exclusively with SMARTanalyzer with the exception of RFD data, which required further processing in MATLAB.

Bar velocity was calculated using the vertical displacement and time data. The concentric and eccentric phases were defined as the time at which the velocity was positive (bar being raised) and negative (bar being lowered), respectively. This definition was held constant throughout all calculations. Force data used in the analysis were found by summing the 2 force platform vertical measurements, yielding a net force in the vertical direction. Peak force occurred at the transition between the eccentric and concentric phases (i.e., at the bottom of the exercise cycle where the bar transitions to the upward movement). Power was calculated from the product of the synchronized bar velocity and net (summed) force data. The peak power values were taken in the concentric phase and occurred in the latter half of the concentric movement.

Values for RFD were observed during 3 different time intervals along the force–time curve, which are displayed in Figure 3; RFD was found by differentiating the force–time curve. The mean RFD was calculated over each of the 3 time intervals to give an accurate representation of the slope within that time. Time intervals A and B represent the mean RFD 0.15 seconds on either side of the PF. Because the PF was always associated with the transition from eccentric to concentric, the mean RFD values represent the last 0.15 seconds of the eccentric phase, and the first 0.15 seconds of the concentric phase. The reason for looking at these values was to assess the effect of the SSC at the bottom of the exercise for each condition, NB and WB. If a steeper spike was present–representing rapid force development from the eccentric to concentric phase–the mean RFD values would be greater and vice versa. Note that in the concentric phase, the RFD in the first 0.15 seconds is negative; thus, a more negative value would represent a steeper (greater) slope (Figure 3). The time duration of 0.15 seconds was chosen by carefully analyzing each subject's force–time curve about the zero-velocity point. The time interval of 0.15 seconds allowed, for all subjects, the greatest number of data points to be analyzed while staying within the unambiguous bell-shaped portion of the force–time curve. Time interval C represents the positive RFD values (from the local minimum to the local maximum) in the concentric phase leading up to the second peak in the force–time curve. This time interval is associated with the force production as subjects began to reach a more favorable biomechanical position.

For all dependent variables, the value for each set was found by taking the greatest value from the 3 repetitions. The 3 set values were then averaged to yield an overall value for each subject in each condition. The averages for each subject in each condition were then averaged to give a final value for both conditions. These final mean values for each condition were used for comparison of the NB and WB conditions. This method was chosen to best represent each of the conditions and exclude possible outlying values because of poor repetitions. An exception to this method was the calculation of the thigh angle. For this value, all 3 repetitions were taken into consideration to yield an overall average for each subject in each condition.

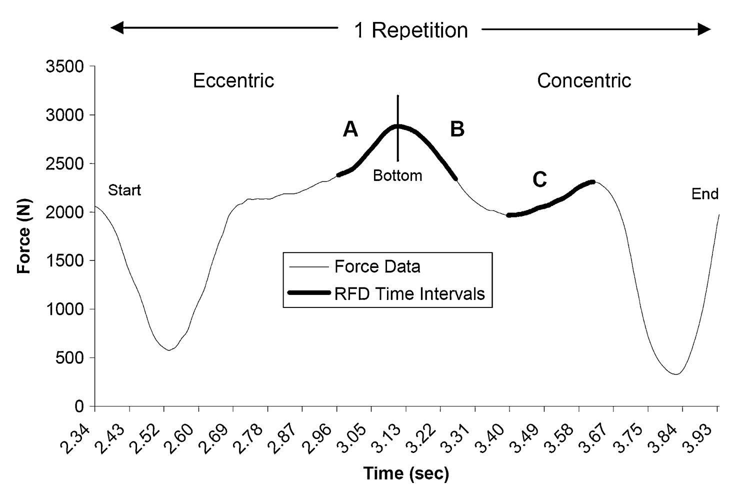


Figure 3. Example of a force–time curve for 1 repetition, with the rate of force development (RFD) time intervals highlighted. A) Last 0.15 seconds of eccentric phase; B) first 0.15 seconds of concentric phase; C) positive RFD in the concentric phase.

Statistical Analyses

Means and *SD*s were calculated for each dependent variable and each condition. Independent variables were defined as the percentage load (55% 1RM) being lifted and the percentage added (20% of the 55% 1RM) because of the elastic bands. The predetermined criterion for statistical significance was set at an alpha level of 0.05.

TABLE 2. Mean ± *SD* values for each dependent variable and condition with the respective *p* value.*†

Dependent variable	Condition		
	No bands	With bands	*p* Value
Peak velocity ($m\cdot s^{-1}$)–concentric	1.33 ± 0.09	1.28 ± 0.11	<0.001
Peak velocity ($m\cdot s^{-1}$)–eccentric	1.38 ± 0.15	1.42 ± 0.19	0.011
Mean velocity ($m\cdot s^{-1}$)–concentric	0.81 ± 0.05	0.79 ± 0.06	0.002
Mean velocity ($m\cdot s^{-1}$)–eccentric	0.79 ± 0.08	0.78 ± 0.09	0.999
Peak force (N)	2,536.97 ± 374.89	2,564.63 ± 396.09	0.168
Peak power (W)–concentric	2,625.14 ± 501.99	2,647.29 ± 504.13	0.477
RFD_A ($N\cdot s^{-1}$)	2,687.94 ± 853.90	2,646.54 ± 994.19	0.745
RFD_B ($N\cdot s^{-1}$)	−3,083.01 ± 1,079.41	−3,090.74 ± 1,269.93	0.950
RFD_C ($N\cdot s^{-1}$)	1,459.27 ± 525.37	1,583.14 ± 525.05	0.028

*RFD = rate of force development; RFD_A = RFD immediately before the zero-velocity point; RFD_B = RFD immediately after the zero-velocity point.

†Significance level is $p < 0.05$. $n = 20$ subjects.

A paired sample *t*-test was conducted for each of the dependent variables to determine whether significant ($p \leq 0.05$) differences occurred between the NB and WB conditions. Means and *SD*s were also computed for biometric and neuromuscular status data. These data were compared using a paired sample *t*-test to ensure the subjects were not statistically different ($p \geq 0.05$) for each of the testing conditions. All of the hypotheses testing calculations were performed with SPSS statistical software for Windows (Version 14.0, SPSS Inc., Chicago, IL, USA).

A multiple variable Pearson correlation was performed to determine the test–retest reliability for the 3 sets performed in each condition for each dependent variable. Correlation coefficients were calculated and are summarized in Table 3. Correlation calculations were performed using Minitab (Version 15.1.1.0, Minitab Inc., State College, PA, USA).

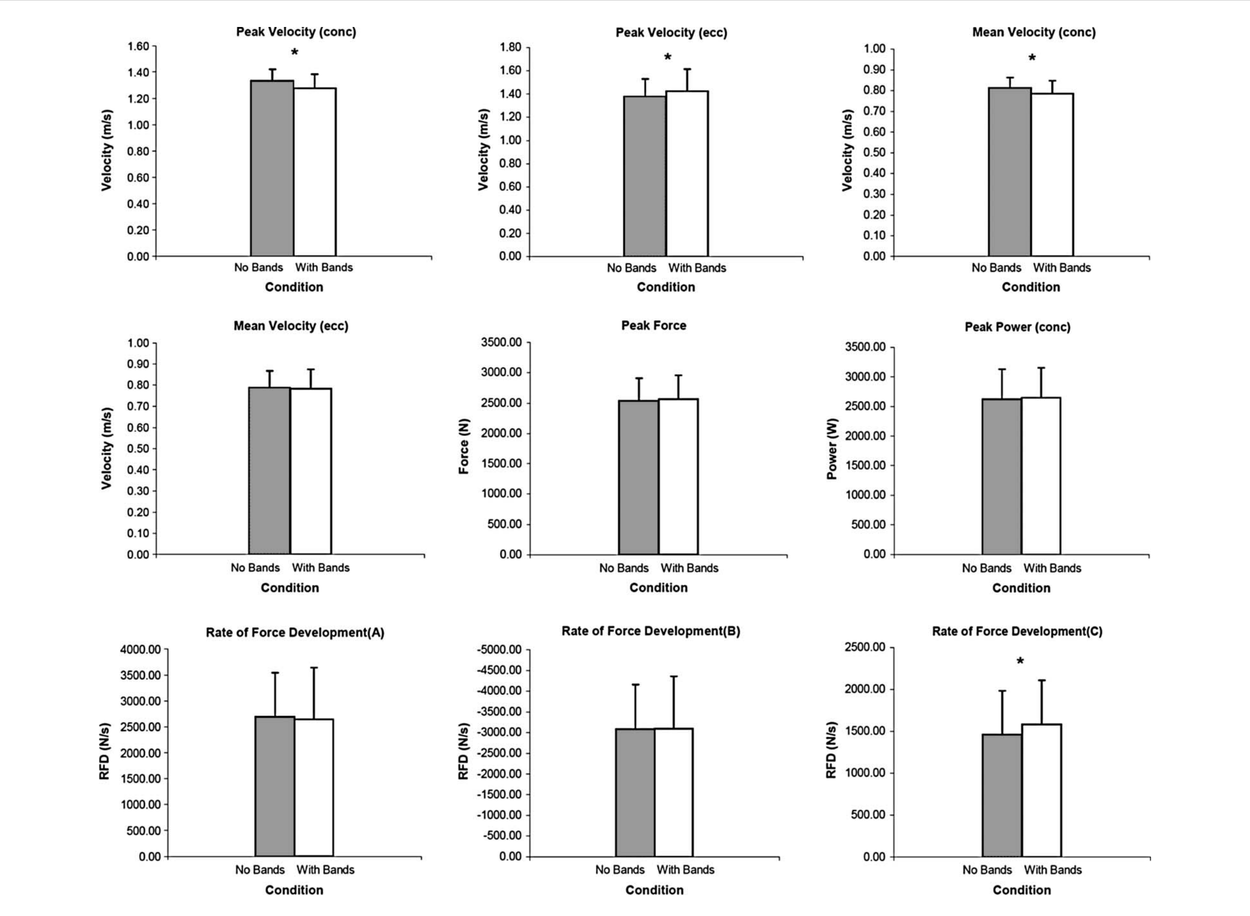
RESULTS

A summary of the means, *SD*s, and *p* values, can be seen in Table 2. Figures 4–12 graphically display the results for each dependent variable. The statistical analysis showed

TABLE 3. Correlation coefficients for the test–retest reliability between the 3 sets performed for each dependent variable in each condition.*

Dependent variable	Condition							
	No bands				With bands			
	Sets 1–2	Sets 1–3	Sets 2–3	Average	Sets 1–2	Sets 1–3	Sets 2–3	Average
Peak velocity ($m\cdot s^{-1}$)–concentric	0.792	0.817	0.913	0.841	0.878	0.798	0.828	0.835
Peak velocity ($m\cdot s^{-1}$)–eccentric	0.747	0.822	0.871	0.813	0.906	0.812	0.889	0.869
Mean velocity ($m\cdot s^{-1}$)–concentric	0.804	0.829	0.867	0.833	0.867	0.802	0.835	0.835
Mean velocity ($m\cdot s^{-1}$)–eccentric	0.837	0.878	0.884	0.866	0.897	0.782	0.935	0.871
Peak force (N)	0.965	0.970	0.974	0.970	0.941	0.944	0.977	0.954
Peak power (W)–concentric	0.918	0.948	0.972	0.946	0.966	0.924	0.918	0.936
RFD_A ($N\cdot s^{-1}$)	0.835	0.841	0.855	0.844	0.739	0.793	0.877	0.803
RFD_B ($N\cdot s^{-1}$)	0.82	0.818	0.841	0.826	0.853	0.612	0.885	0.783
RFD_C ($N\cdot s^{-1}$)	0.782	0.877	0.713	0.791	0.813	0.828	0.766	0.802
Overall correlation coefficient				0.859				0.854

*RFD = rate of force development; RFD_A = RFD immediately before the zero-velocity point; RFD_B = RFD immediately after the zero-velocity point.



Figures 4–12. Graphical presentation of the results for each dependent variable. *Significant ($p < 0.05$) difference between NB and WB conditions ($n = 20$ subjects).

significant differences between the NB and WB conditions for 4 of the nine dependent variables observed: PV-C; PV-E; MV-C; and RFD_C. In support of our hypothesis, PV-E and RFD_C were significantly greater in the WB condition than in the NB condition ($p = 0.011$, $p = 0.028$, respectively). In contrast to our hypothesis, however, PV-C and MV-C were significantly greater in the NB condition than in the WB condition ($p < 0.001$, $p = 0.002$, respectively). The remaining dependent variables (MV-E, PF, PP, RFD_A, RFD_B) did not show significant differences ($p \geq 0.05$) (Table 2). Correlation coefficients for the test–retest reliability of the 3 sets performed can be seen in Table 3. The average overall coefficients for the NB and WB conditions were 0.859 and 0.854, respectively.

No significant differences ($p \geq 0.05$) were found between each testing day for either the subject neuromuscular status (VJ, HD) or body weight data. The average differences between the testing conditions for each subject were: VJ: 1.97 ± 1.27 cm; HD: 2.95 ± 2.19 kg; weight: 0.73 ± 0.47 kg. In addition, there was no significant difference ($p \geq 0.05$) between the depths of the squat (indicated by the thigh angle measurement) for each testing condition: NB: 79.59° ± 8.42°; WB: 78.19° ± 9.57°.

Discussion

Anecdotal claims from strength coaches and other practitioners indicate that training with elastic bands in certain exercises is more effective at eliciting strength and power gains than traditional methods alone (38–40). However, the relatively small amount of previous research on the topic has yielded conflicting results. Ebben and Jensen (16) found no differences in GRFs between regular back squats and squats performed with bands, whereas Wallace et al. (42) showed that peak power and PF were greater when bands were incorporated compared to the constant load condition. The findings of the current study also yield conflicting results. In the present study, it was hypothesized that the use of bands creates an overspeed eccentric phase that elicits a greater response from the SSC and translates to improved power development, RFD, and velocity in the concentric phase. In general, the results of this study do not support our hypothesis and refute anecdotal claims. Only the peak velocity in the eccentric phase and RFD in the concentric phase were significantly greater in the squats performed with bands as compared to without bands. Additionally, the fact that mean and peak velocities in the concentric phase were greater without bands suggests that bands actually hinder concentric velocities in the squat.

In support of the hypothesis, peak velocity in the eccentric phase (PV-E) was significantly greater in the WB condition than the NB condition. This can be explained by the fact that the bands imparted a greater force to the bar and therefore caused a greater acceleration of the bar in the eccentric phase. This would be particularly evident in the beginning portion of the eccentric phase when the bands exerted the greatest tension. However, mean velocity in the eccentric phase (MV-E) was not significantly affected, which is in contrast to the hypothesis, and suggests that no overspeed eccentric phase occurred. One possible explanation for this seemingly contradictory finding is that there may be a more pronounced deceleration phase toward the end of the eccentric portion of the lift to counteract the greater peak velocity. It is possible that there is some protective mechanism that subconsciously controls the eccentric velocity and does not allow individuals to exceed a particular threshold regardless of the magnitude or type of load. Over many years some highly trained individuals develop an ability to alter this threshold and therefore have the ability to descend faster with greater or varying loads.

Both peak and mean velocities in the concentric phase (PV-C and MV-C, respectively) were significantly greater in the NB condition than in the WB condition; this finding, although significant, is in opposition to the hypothesis. A possible reason for this may be that peak velocities were found to occur at an approximate thigh angle of 50°, which represents a stage that the elastic bands were exerting additional force. This additional force (compared to the same point in the NB condition) likely had a deceleration effect that would have reduced both peak and mean velocities in the WB condition. These results do not support the idea that using elastic bands in the squat produces increased velocity in the concentric phase because of an exploitation of the SSC. Interestingly, if velocity is an important performance variable as some have suggested (23), these findings actually support the traditional mode of constant resistance.

Peak force was not significantly different between the 2 conditions and was always attained at the bottom position of the squat during the transition between the eccentric and concentric phases (i.e., coupling phase). This was also in contrast to the hypothesis and further suggests that there was no overspeed eccentric phase elicited by the incorporation of bands. Had an overspeed eccentric phase occurred, it would have likely been reflected by the PF at the reversal point. For example, if the overall eccentrics phase had been faster (i.e. greater MV-E), a greater deceleration would have been required to slow the bar to a stop and reverse the movement into the concentric phase. To generate a deceleration of a greater magnitude, a greater force would have been required, simply based on Newton's second law ($F = ma$). Because no difference in PF was seen in the present study, it is possible to conclude that no overspeed eccentrics were observed in the WB condition.

No significant differences were observed in peak power between the 2 experimental conditions, which does not support the hypothesis. Peak power, as opposed to mean power, was measured because of its stronger correlation to performance (15). At the time of peak power in the concentric phase, which occurred near the time of peak velocity, it is important to note that the bands were engaged. Because power equals force times velocity, and the values of both experimental conditions were very close, it was inferred that at the time of peak power, there was relatively less force and greater velocity in the NB condition and greater force and relatively smaller velocity (because of the engaged bands) in the WB condition. These inferences, with respect to velocity, are in agreement with the results observed for PV-C and MV-C. A great deal of research has focused on the loads and training strategies necessary to optimize power output (5,9,12,13,15,21,22,24,33,36,41,42,45). The fact that no difference was detected in peak power between the 2 conditions does not support the premise that training with bands is more effective than using traditional modes for optimizing power output.

Rate of force development was examined at 3 separate time intervals, which is a unique aspect of this study. The first 2 intervals represent the time periods corresponding to 0.15 seconds immediately before (RFD_A) and after (RFD_B) the zero-velocity point (reversal point). These time intervals, A and B, best represent the SSC surrounding the reversal point for all subjects and allow for the maximum number of data points to be analyzed without going outside of the clearly defined bell-shaped portion of the force–time curve (Figure 3). There was no difference in either RFD_A or RFD_B between the 2 conditions that is in opposition to the hypothesis. Because this is the point at which the loads were equal between the NB and WB conditions, significantly greater RFD values during the A and B time intervals would have been strong evidence in support of an overspeed eccentric phase and augmented SSC effect. RFD_C was defined as the positive RFD in the concentric phase and corresponded to the time interval at which subjects were in a more biomechanically favorable position for force production. RFD_C was found to be significantly greater when bands were incorporated; however, based on the current results, this finding cannot be attributed to an enhanced SSC and overspeed eccentrics. Rather, although the exact mechanism remains unclear, the current findings lend support to the notion that VRT in the form of elastic bands may be effective in increasing RFD in the concentric phase, and numerous authors have stated that RFD is particularly important because it relates to performance (1,3,20).

A differentiating and important aspect of the current study was the methodology by which data were collected and analyzed, which was largely because of the instrumentation used in this study. In particular, the advantages of the 9-camera motion capture system include independent and synchronized displacement and force data, purely vertical displacement data from a multidimensional movement (free weights), and quantitative depth measurement of the squat. In addition to the instrumentation used for the collection, the VJ and HD muscular/neuromuscular tests were unique to this study and ensured that subjects were at similar capability levels for each of the testing conditions.

Other studies have reported using only a single measurement source–either a force platform or a displacement measuring device–for calculating variables that require both displacement and force data, such as power ($P = F \times V$) (5,42). This method of collection has been criticized for the data manipulation required to reach such values (15,21). The use of either force or displacement data requires double integration or differentiation, respectively, to determine the power values, which can lead to less accurate results (15). The current study used the 9-camera motion capture system for displacement data, and 2 independent force plates (1 for each foot) for the collection of force data, thus following the recommended methodology (15,21).

Another advantage of the 9-camera motion capture system is that it can extract sole vertical displacement data from the 3-dimensional motion of a free-weight back squat. Commonly, studies use a single linear position transducer for collecting free-weight squat displacement data (5,44). This methodology has been subject to criticism, however, because it conjugates *x*-direction (anterior–posterior) and *z*-direction (lateral–medial) motion with the vertical direction motion (9). This can lead to less accurate displacement and velocity measures. Other studies have used Smith machines, which constrain the movement of the bar to the single vertical plane (10,30,36). This method has an obvious disadvantage in that it does not accurately represent the common free-weight squat used in training and does not mimic the multidimensional movement of sport.

In addition, the majority of studies that involve a squat exercise do not specify nor quantify the depth to which the subjects descend during the movement (5,9,42,45). The advantage of the 9-camera motion capture system was that it could quantify the depths of each subject using reflective markers on the hip and the knee. The results showed an average depth that was consistent between both conditions (NB: 79.59° ± 8.42°; WB: 78.19° ± 9.57°) and a very low average difference between the NB and WB conditions for each subject (3.33° ± 2.92°). These results suggest that the bands had a minimal effect on the range of motion of the exercise and that the depth between each condition was not a contributing factor for the observed differences in dependent variable values. Although every subject was instructed to go down to a depth such that the top of the thigh's were parallel to the floor–and thus the vector from the knee marker to the hip marker would be parallel to the floor–interestingly, our results show that on average the subjects did not reach 90°. This finding suggests that either (a) beginning to intermediate level individuals do not (or cannot), in general, descend to depths approximate to the thigh being parallel to the ground, or (b) people generally perceive they are descending to greater depths than they really are.

One unique aspect of this study was the use of neuromuscular testing to assess each subject's status. It was thought that any major differences in subjects' muscular fatigue levels or neuromuscular status from 1 testing day to the next would be manifested by differences in maximal vertical jumping or isometric HD. It was also assumed that the performance of the 2 tests before doing the squats would not significantly fatigue the subjects. A difference in performance on either of the 2 tests would have indicated reduced potential for an absolute maximal effort because of fatigue or other factor(s). The fact that there were no differences between the 2 testing days for either test indicates that the potential for a maximal effort was similar. The relationship between neuromuscular testing and performance is a potentially beneficial tool for researchers and practitioners alike; however, more study in this area is needed. If a strong correlation is indeed shown to exist between the performances of a VJ or HD test and potential for maximum performance, it would be invaluable to conduct these tests not only in research settings but also in the field. Training variables could then be manipulated daily and individually based on fatigue levels that may not be otherwise apparent or visible.

However, there were limitations to this study: The first was that the bands were never fully slacked at the bottom of the squat in 4 subjects. In addition, the bands did not slacken or tense up at the exact same relative point during the range of motion for any 2 subjects. The overall results of the study were likely not significantly altered because only 4 subjects did not experience a complete unloading of the bands and only minimal tension was present in these cases. This limitation was caused by using the same pair of bands for each subject and effectively shortening the band to increase tension. For example, the particularly strong subjects required a greater number of band loops around the bar (see Figure 2) to achieve the prescribed band tension in the upright position. Because the bands were shortened to such a degree for the stronger subjects, a complete relaxation of the bands was not achieved in the bottom position. Using varying thicknesses of elastic bands (based on strength levels) would have solved the problem of the "slackness" at the bottom of the squats but would have produced a new quandary in that the rate of tension development would have been different between differing thicknesses of bands. Custom-made bands with lengths and thicknesses based on individuals' strength levels and dimensions is 1 suggested way to improve upon this limitation.

Another limitation of the study was the heterogeneity of the subjects. The majority of subjects were classified as intermediate in terms of ability and experience. However, a few subjects were advanced as evidenced by their experience in competitive power lifting and Olympic weightlifting. It is possible that the results may have been different if all subjects fell within a particular experience and ability level. This classification can be difficult to quantify but is a consideration nonetheless, especially in light of the fact that much of the anecdotal evidence that supports the use of elastic bands has come from elite-level strength athletes (38–40). Finally, although it is clear that most subjects did not achieve the desired squat depth, this is not considered a limitation because each subject went down to the same depth in both conditions. The 1 caveat to this is the relationship of the SSC to squat depth. Although it is a viable conclusion that a deeper squat may have different implications related to the SSC phenomenon, this remains to be fully elucidated.

In conclusion, performing free-weight back squats with a load of 55% 1RM plus an additional force equal to 20% of the 55% 1RM load (provided by elastic bands) does not appear to elicit the favorable acute performance changes that have been reported anecdotally. The loads and elastic band tensions used in this study do not appear to induce an overspeed eccentric phase, and the SSC phenomenon does not appear to be significantly altered. The salient findings indicate that although there was an increase in RFD in the concentric phase and an increase in peak eccentric velocity using elastic bands, the mean and peak concentric velocities were greater when squats were performed without bands. The conflicting results of this study highlight the need for more research on the topic of VRT in general and elastic bands specifically. In particular, greater band resistance is an area that should be explored across all experience and ability levels.

PRACTICAL APPLICATIONS

This study calls into question the claims made about the elastic band method of VRT. The results suggest that training with moderate loads combined with moderate band tension does not confer any additional overall benefits to those of traditional techniques. However, this study does provide evidence that RFD may be positively affected by training with bands; for individuals interested in this specific parameter, it may be advantageous to consider incorporating this easily implemented training variation. Additionally, using elastic bands with compound movements like the barbell back squat and bench press may allow for more ballistic-type training typically relegated to plyometrics (8,37). This could then allow for the *intention* to produce a maximal velocity through the entire concentric range of motion that some believe to be more important than the actual movement velocity (7). Conversely, because the findings of this study indicate that concentric velocity is negatively influenced by elastic band training, practitioners interested in enhancing velocity-related components should be cautious of band training.

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