THE EFFECTS OF ECCENTRIC CONTRACTION DURATION ON MUSCLE STRENGTH, POWER PRODUCTION, VERTICAL JUMP, AND SORENESS

JONATHAN N. MIKE,[1] NATHAN COLE,[1] CHRIS HERRERA,[1] TRISHA VANDUSSELDORP,[1] LEN KRAVITZ,[1] AND CHAD M. KERKSICK[2]

[1]Department of Health, Exercise, and Sports Science, University of New Mexico, Albuquerque, New Mexico; and [2]School of Health Sciences, Lindenwood University, St. Charles, Missouri

ABSTRACT

Mike, JN, Cole, N, Herrera, C, VanDusseldorp, T, Kravitz, L, and Kerksick, CM. The effects of eccentric contraction duration on muscle strength, power production, vertical jump, and soreness. *J Strength Cond Res* 31(3): 773–786, 2017—Previous research has investigated the effects of either eccentric-only training or comparing eccentric and concentric exercise on changes related to strength and power expression, but no research to date has investigated the impact of altering the duration of either the concentric or the eccentric component on these parameters. Therefore, the purpose of this study was to assess the duration of eccentric (i.e., 2-second, 4-second vs. 6-second) muscle contractions and their effect on muscle strength, power production, vertical jump, and soreness using a plate-loaded barbell Smith squat exercise. Thirty college-aged men (23 ± 3.5 years, 178 ± 6.8 cm, 82 ± 12 kg, and 11.6 ± 5.1% fat) with 3.0 ± 1.0 years of resistance training experience and training frequency of 4.3 ± 0.9 days per week were randomized and assigned to 1 of 3 eccentric training groups that incorporated different patterns of contraction. For every repetition, all 3 groups used 2-second concentric contractions and paused for 1 second between the concentric and eccentric phases. The control group (2S) used 2-second eccentric contractions, whereas the 4S group performed 4-second eccentric contractions and the 6S group performed 6-second eccentric contractions. All repetitions were completed using the barbell Smith squat exercise. All participants completed a 4-week training protocol that required them to complete 2 workouts per week using their prescribed contraction routine for 4 sets of 6 repetitions at an intensity of 80–85% one repetition maximum (1RM). For all performance data, significant group × time (G × T) interaction effects were found for average power production across all 3 sets of a squat jump protocol ($p = 0.04$) while vertical jump did not reach significance but there was a trend toward a difference (G × T, $p = 0.07$). No other significant ($p > 0.05$) G × T interaction effects were found for the performance variables. All groups showed significant main effects for time in 1RM ($p < 0.001$), vertical jump ($p = 0.004$), peak power ($p < 0.001$), and average power ($p < 0.001$). Peak velocity data indicated that the 6S group experienced a significant reduction in peak velocity during the squat jump protocol as a result of the 4-week training program ($p = 0.03$). Soreness data revealed significant increases across time in all groups at both week 0 and week 4. Paired sample *t*-tests revealed greater differences in soreness values across time in the 2S group. The results provide further evidence that resistance training with eccentrically dominated movement patterns can be an effective method to acutely increase maximal strength and power expression in trained college age men. Furthermore, longer eccentric contractions may negatively impact explosive movements such as the vertical jump, whereas shorter eccentric contractions may instigate greater amounts of soreness. These are important considerations for the strength and conditioning professional to more fully understand that expressions of strength and power through eccentric training and varying durations of eccentric activity can have a significant impact for populations ranging from athletes desiring peak performance.

KEY WORDS force production, contraction, performance, neural

INTRODUCTION

Dynamic muscular contractions can be characterized by 2 primary actions, concentric and eccentric contractions. A concentric contraction results in muscle shortening and occurs when the force produced during a contraction exceeds the force applied to the muscle. Alternatively, an eccentric contraction occurs when the muscle is forcibly lengthened or elongated. An eccentric contraction results when the force produced inside the muscle is less than what is applied to the muscle externally (9) and results in active lengthening of the muscle

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Address correspondence to Dr. Jonathan N. Mike, jonathannoahmike@hotmail.com.

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fibers under some level of load. When directly compared, eccentric muscle actions are able to produce greater force, an amount estimated to be 20–60% higher than concentric strength levels (23), and in the same respect, lower levels of neural activation have been shown in eccentric contractions when compared with concentric efforts (42). Evidence surrounding muscle damage (loss of force production, increased soreness, and myocellular protein accumulation in the serum as well as Z-disk streaming) is routinely reported to a greater extent when eccentric contractions are completed (35,36). Finally, some evidence also indicates that a greater contribution from eccentric contractions may better facilitate phenotypic adaptations, such as increased strength and hypertrophy (39). Taken together, all of this evidence suggests that increasing the incorporation of eccentric efforts into resistance training programs for fitness, athletic, and clinical populations may improve in training outcomes.

Researchers routinely report that lower levels of neural activation (42) occur during eccentric contractions when compared with concentric efforts, providing some level of indication that typical loading patterns used as part of resistance exercise prescriptions might be dependent on the muscle actions involved. Eccentric resistance training incorporating submaximal, maximal (100% one repetition maximum [1RM]), or supramaximal (>100% 1RM) training loads have been shown to stimulate greater increases in maximal muscle strength (22,24,25,34,41) compared with conventional types of strength training (10), or using very light loads of resistance training (5). In addition, and while both concentric and isometric muscle contractions elicit a hypertrophy response, numerous studies have reported that eccentric actions may have the greatest effect on skeletal muscle growth (20,24,25,32,38). Importantly, some studies go one step further and indicate that the speed of the eccentric contraction may have a predominant influence over the resulting hypertrophy (19,45). Thus, from a hypertrophy perspective, it seems that movement speed during the eccentric portion of a repetition may play a significant role in determining how the involved muscle responds. Most recently, it was concluded that slow speed of movement (4-second eccentric actions during bicep curls produced superior increases in arm growth vs. a 1-second eccentric action and even concentric action of 1-second), and improved, hypertrophy in well-trained adults (37).

When looking closely at the impact of contraction speed, most work has centered upon the entire eccentric-concentric contraction of varying speeds with little to no work focused on the specific impact of altering the contraction speed and duration of only part of the contraction cycle (concentric only or eccentric only). In this respect, resistance training regimens that involve a rapid production of force can impact changes in the rate of force development (RFD) and resulting power production (31). Increases in power production have been shown to result from slower-speed training along with increases in agonist muscle activation (2). For example, Blazevich (3) examined the effects of slow-speed resistance training involving concentric vs. eccentric on contractile RFD involving isometric knee extension. They found that subjects with a lower ability to rapidly attain their maximum force before training improved RFD with slow-speed resistance exercise (3). Furthermore, a meta-analysis by Roig et al. (38) compared the effectiveness of exercise modalities at eliciting muscular adaptations, and he reported that high-intensity eccentric training was associated with greater muscular adaptations than concentric training, but the impact of changing the duration of the eccentric contractions remains undetermined.

In addition to force production dynamics and neural contributions, available literature indicates that acute bouts of eccentric contractions elicit greater muscle damage compared with concentric training (35,36), which is commonly assessed by evaluating changes in force production, self-reported soreness, and serum levels of creatine kinase (28,48,52). Moreover, a recent review suggests that some level of damage may be needed to facilitate other adaptations such as muscle hypertrophy (39), which supports the need to better understand how manipulations of eccentric contractions may impact resulting physiological adaptations.

Finally, many studies have used isokinetic dynamometers to execute the isokinetic eccentric actions. Although valuable for their ability to control the contraction speed, laboratory-based isokinetic measurements are expensive, lack portability, and typically only use single-joint muscle actions (e.g., knee extension or elbow flexion) that are difficult to replicate to real-world resistance training situations. Therefore, the purpose of this study was to examine the impact of 4 weeks of eccentric training at a load equivalent to 80% 1RM using different durations of eccentric contractions using a commercially available Smith machine squat rack on charges related to strength, power production, vertical jump, and soreness.

METHODS

Experimental Approach to the Problem

Using a randomized, repeated-measures design, with parallel independent groups, this study examined the impact of eccentric contraction duration as part of an eccentric training program for changes in strength, power production, vertical jump, and soreness parameters. After assessing inclusion criteria and signing institutional review board–approved consent forms, subjects initially completed a familiarization session where they practiced vertical jump testing, determined their 1RM, and performed the power testing protocol. Upon completion of the familiarization session, all study participants completed a 4-day dietary record and had their body composition determined using skinfolds for demographic purposes before beginning the study protocol. Thirty healthy, college-aged men (23 ± 3.5 years, 178 ± 6.8 cm, 82 ± 12 kg, 12 ± 5.1% fat) with 3.0 ±

1.0 years of resistance training experience and an average weekly training frequency of 4.3 ± 0.9 days per week. In a randomized fashion, participants were assigned to 1 of 3 exercise groups that required them to complete all prescribed repetitions with different durations of eccentric contractions using the barbell Smith squat exercise. The first group used a traditional concentric-eccentric training duration consisting of 2-second concentric contractions, a 1-second pause, and a 2-second eccentric contraction (40). This group is referred to as the 2S group ($n = 10$) and operated as a control group in our study design. The second group (4S, $n = 9$) performed 4-second eccentric contractions (2-second concentric contraction, 1-second pause, and 4-second eccentric contraction), whereas the third group (6S, $n = 11$) completed 6-second eccentric contractions (2-second concentric contraction, 1-second pause, and 6-second eccentric contraction). All exercise training sessions occurred at approximately the same time each day. Subjects completed an eccentric exercise protocol consisting of 4 sets of 6 eccentric contractions of the barbell Smith squat exercise using 80–85% 1RM. Experienced strength and conditioning professionals supervised every repetition and provided verbal and auditory cues using a metronome to instruct each participant on their required cadence for each repetition. No rest was provided between repetitions and 3 minutes of rest was used between sets. Each participant completed 4 weeks of training at a frequency of 2 days per week with each workout being separated by 72 hours. Thus, each participant completed a total of 8 workouts. To assess both the acute and the prolonged impact of training with different durations of eccentric contractions, measurements were taken to assess strength, power, and vertical jump before the first workout and after the final workout. In conjunction with previous literature that has reported on increases in muscle soreness in response to eccentric contractions (8,28), each subject provided their level of soreness using a visual analog scale before, immediately after training, and 24, 48, and 72 hours after completion of their first and final workouts. To assess changes in power production, each subject had their vertical jump determined before (pre) completion of their first workout and after the final workout. All testing sessions were standardized for all subjects allowing for 72 hours of recovery between the final workout and posttesting measurements.

Subjects

All data collection was conducted at the Exercise Physiology Laboratories at the University of New Mexico (Albuquerque) at an altitude of 1,600 m (5,400 ft) and an approximate barometric pressure of 630 mm Hg. Subjects for this investigation included 30 resistance-trained, college-aged men (23 ± 3.5 years, 178 ± 6.8 cm, 82 ± 12 kg, and 11.6 ± 5.1% fat) with 3.0 ± 1.0 years of resistance training experience and a training frequency of 4.3 ± 0.9 days per week. Recruitment centered largely upon university physical activity classes and local gyms and fitness centers. A resistance training questionnaire was used to assess each subject's resistance training background, which consisted of 5 multiple choice questions regarding frequency of training, length of training (years) overall intensity used during each workout, and current involvement with lower-body training. This procedure was completed for inclusion criteria and participants were considered resistance trained if they had completed a minimum of 3 days of resistance training per week for at least 3 years or more, which included some combination of lower-body resistance exercise, team sport participation, or regular participation in endurance exercise, such as running or cycling. All participants were previously resistance trained, had similar resistance training experience, and were currently not participating in regular aerobic exercise. Subjects were tested in the Exercise Physiology Laboratories at the University of New Mexico (Albuquerque) in a controlled training environment with no music and without a large audience effect. In addition, each subject was required to read and sign an institutional review board-approved informed consent document and complete a physical activity readiness questionnaire (PAR-Q). Participants were further asked to: (a) avoid changes in their diet and medication use (both over-the-counter and prescription). In particular, nonsteroidal anti-inflammatory drugs, cox-2 inhibitors, or acetaminophen were strictly forbidden within the first 72 hours of completing the first and last workouts, (b) abstain from intense, unfamiliar physical activity for 48 hours before each testing session, and (c) avoid caffeine or nicotine use 12 hours before each exercise session. To minimize any confounding impact of other exercise stimuli, all participants were required to abstain from any training of the lower body (including running, cycling, jogging, etc) outside the intervention for the duration of the study, and all other forms of training were to remain consistent throughout the intervention.

Exclusion criteria for this study were those participants diagnosed with or being treated for any cardiovascular, renal, metabolic, hepatic, immunological, orthopedic, psychological, pulmonary, respiratory, or musculoskeletal disorder. Individuals who took any dietary supplements or performance-enhancing drugs known to increase resistance-training performance (i.e., creatine or anabolic agents) with the exception of a multi-vitamin and dietary protein were excluded. Participants who regularly took any nonsteroidal anti-inflammatory drugs (i.e., ibuprofen, aspirin, etc.) and those individuals who were sedentary were also excluded. Finally, all female participants were excluded from this study because of the monthly physiological and hormonal changes that occur, which can induce a confounding influence, specifically their impact on muscle damage (47,51).

Procedures

Eccentric Exercise Protocol. To reduce the impact of confounding variables associated with the completion of other forms of activity, all participants were required to abstain from any additional resistance training activities using the lower body outside the study protocol for the duration of the study, and all other forms of training were to remain consistent throughout the intervention. Using a training protocol of 2 days per week over a 4-week period, all study participants completed 8 workouts consisting of 4 sets of 6 repetitions with varying durations of eccentric contractions. All repetitions were completed using a plate-loaded barbell Smith squat exercise with a resistance level that equated to 80–85% 1RM. All workouts were separated by 72 hours, meaning that all participants followed either a Monday-Thursday, Tuesday-Friday, or Wednesday-Saturday approach. All exercise training sessions occurred at approximately the same time each day, and each repetition was supervised by trained investigators using a metronome to assist with the correct phase for each repetition. All study participants were randomized into 1 of 3 training groups. The first group was considered a control group (2S) and completed all repetitions using a traditional concentric-eccentric contraction pattern (2-second concentric, 1-second pause, and 2-second eccentric). The second group (4S) completed all workouts using a similar contraction pattern while incorporating a 4-second eccentric contraction (2-second concentric, 1-second pause, and 4-second eccentric). The third group (6S) completed all workouts using a similar contraction pattern while incorporating a 6-second eccentric contraction (2-second concentric, 1-second pause, and 6-second eccentric contraction). No rest was allowed between each repetition, and a rest period of 3 minutes was observed between completed sets. On a workout-by-workout basis, and in the event any study participant was unable to adhere to the prescribed contraction duration, the prescribed load was reduced by 10%, and all remaining repetitions were completed at the revised resistance level and at the same contraction duration.

Nutritional Control. No specific control over dietary habits was used for this study protocol. Before beginning the protocol, all participants completed 4-day (3 week days and 1 weekend day) dietary records by recording all food and beverage consumed. All participants were asked to avoid changes to their diet and were strictly forbidden from adding any dietary supplements or adopting any dietary strategy that might impact their muscle's response to all workouts and the associated training adaptations. All data were entered into a freely available online nutrition database for determination (MyFitnessPal) of average energy and macronutrient intake. It was highly recommended that study participants adhered to and consumed a diet that was easy to replicate and was a typical representation of their normal diet. Copies of all dietary logs were made and provided to the participants for them to replicate their diet leading up to each testing session. The night before those study visits, subjects were advised to eat no later than 22:00 hours and abstain from caffeine, nicotine, or alcohol use for a 24-hour period. Participants were also advised to abstain from intense, unfamiliar physical activity and exercise for 48–72 hours before each testing session.

Body Composition and Anthropometry. For descriptive purposes only, a standard stadiometer was used to record the participants' height in centimeters and weight was measured in pounds (lbs), and converted to kilograms (kg). After height measurement, the participants' body fat percentage was determined before the completion of the 4-week eccentric training period using skinfold calipers (Lange). The sum of 3 skinfold sites (chest, abdomen, and thigh) was used to estimate body density (27) before being converted to percent body fat using the Brozek equation (4). All measurements were taken on the right side of the body and read to the nearest 0.5 mm (Beta Technology, Cambridge MD, USA). A minimum of 2 measurements were taken at each site using rotational order with the skin dry and lotion free. If the values varied by more than 2 mm, additional measurements were taken.

One Repetition Maximum Testing. A 1RM was performed by all study participants before (pre), midway through, and after (post) the eccentric training program (9). All 1RMs were determined using a standard barbell Smith squat exercise. The 1RM testing began with 2 sets of 10 repetitions using a resistance that equates to 50% of self-reported 1RM before completing an additional warm-up set at 80% of self-reported 1RM. Using standard National Strength and Conditioning Association (NSCA) guidelines (1), the load was increased 10–20% using 1-repetition sets until only 1 successful repetition was completed. To minimize any negative influence of fatigue, each participant's 1RM was determined in approximately 3–5 1RM attempts. A lift was deemed successful if a squat repetition was performed to a depth of an 80–90° knee angle and confirmed by visual inspection with trained investigators. The greatest load lifted without assistance and through a full range of motion was recorded as the subject's 1RM. Subjects were instructed not to train for at least 48 hours before determining their 1RM. To minimize the influence of a learning effect on 1RM performance, study participants completed a familiarization session before beginning the training program where they were required to determine their 1RM according to study protocol.

Power Production and Testing. To determine peak and average power production and peak velocity of movement, a Tendo Power and Speed Analyzer (Software Version-multi-station Net-V-104; TENDO PSA 310, Europe, Slovak Republic) was used and attached to the barbell with an extended nylon cord and Velcro strap. The Tendo unit was placed on the floor in a position that allowed the cord to be extended perpendicular to the floor during the Smith squat exercise movement in accordance with the Tendo weightlifting

Table 1. Descriptive statistics for all study participants (mean ± *SD*).*

	2S ($n = 10$)	4S ($n = 9$)	6S ($n = 11$)	All groups ($n = 30$)	Sig. (p)
Age (y)	22 ± 2.1	22 ± 2.1	23 ± 4.2	23 ± 3.5	0.21
Height (cm)	180 ± 6.6	176 ± 4.8	178 ± 8.4	178 ± 6.8	0.58
Weight (kg)	79 ± 5.4	82 ± 12.0	85 ± 16.7	82 ± 12	0.57
Body fat (%)	10.3 ± 3.6	10.5 ± 4.8	13.7 ± 6.0	11.6 ± 5.1	0.23
Standing reach (cm)	226 ± 9	223 ± 8	228 ± 13	226 ± 11	0.66
Training experience (y)	3.1 ± 0.9	2.8 ± 1.1	3.1 ± 1.0	3.0 ± 1.0	0.73
Training frequency ($d \cdot wk^{-1}$)	3.9 ± 0.9	4.4 ± 1.0	4.6 ± 0.7	4.3 ± 0.9	0.21
One repetition maximum (kg)	124 ± 20.0	129 ± 22	118 ± 17	123 ± 19	0.44
Energy intake ($kcal \cdot d^{-1}$)	2,424 ± 482	2,907 ± 501	2,658 ± 1,005	2,655 ± 726	0.36
Carbohydrate intake ($g \cdot d^{-1}$)	247 ± 46	276 ± 62	286 ± 134	270 ± 91	0.60
Protein intake ($g \cdot d^{-1}$)	133 ± 44	214 ± 70	166 ± 68	169 ± 68	*0.03
Fat intake ($g \cdot d^{-1}$)	93 ± 30	105 ± 42	101 ± 42	99 ± 37	0.78
Relative energy intake ($kcal \cdot kg^{-1} \cdot d^{-1}$)	36.3 ± 17.9	30.6 ± 14.7	28.7 ± 15.7	31.8 ± 16.0	0.55
Relative carbohydrate intake ($g \cdot kg^{-1} \cdot d^{-1}$)	3.2 ± 0.6	3.0 ± 1.4	2.0 ± 0.6	3.1 ± 1.4	0.90
Relative protein intake ($g \cdot kg^{-1} \cdot d^{-1}$)	2.3 ± 2.0	2.4 ± 1.4	1.8 ± 1.1	2.1 ± 1.5	0.66
Relative fat intake ($g \cdot kg^{-1} \cdot d^{-1}$)	1.32 ± 0.6	1.15 ± 0.7	1.08 ± 0.6	1.18 ± 0.6	0.68

*One-way analysis of variance, $p \leq 0.05$.

analyzer. To calculate power, the amount of resistance placed upon the bar and lifted (in kilograms) was entered into the software, and using the data in conjunction with the distances traveled and time required to traverse the distance, power was estimated. Using proper squatting technique and a resistance equating to approximately 45% 1RM (30), participants completed 3 sets of 5 jump squat repetitions. A rest period of 3 minutes was observed between sets (50).

Subjects were instructed to hold a bar of the corresponding weight (45% 1RM) on their shoulders in the back squat position. Performance of the jump squat for measuring power production involved lowering the bar to the point where the knee angle was approximately 100° as measured by a goniometer. After reaching the bottom of the movement, participants were instructed to immediately jump upward as fast as possible with their feet leaving the ground while holding the bar tightly to the shoulders for 5 consecutive repetitions. Each subject was allowed multiple practice repetitions with immediate feedback from the investigators to maintain safe and proper technique. Peak velocity generated during the concentric phase of each repetition was recorded by the Tendo unit and the repetition(s) responsible for generating the greatest power output.

Perceived Soreness. Before and 0, 24, 48, and 72 hours after the first and last workouts of the eccentric protocol, subjects were asked to assess their perceived level of muscle soreness using a visual-analog scale. Soreness was evaluated along a 10-cm scale (0 cm = no soreness, 10 cm = extreme soreness) at all indicated time points by drawing a line perpendicular to the continuum line extending from 0 to 10 cm. The distance of each mark was measured from zero and rounded up to the nearest one-tenth of a centimeter. This method of assessing perceived soreness has been used in a number of previous investigations and is commonly accepted for this purpose (8,28).

Table 2. Training progression for all workouts, sets, reps, and % 1RM over 4-week training period.*†

Sessions	1–4	Before session 5, retest 1RM for all subjects	5–8
No. sets	4		4
% 1RM	80%		85%
Repetitions	6		6
Eccentric duration (s)	2, 4, or 6		2, 4, or 6

*1RM = 1 repetition maximum.

†Workouts 1–4 incorporated 80% 1RM for all groups. Workouts 5–8 incorporated 85% 1RM for all groups. Training frequency was 2× per week with 72-hour recovery between sessions.

Vertical Jump. Before completing the first workout, and after the final workout, vertical jump height was assessed. The Vertec (Jump USA, Sunnyvale, CA, USA) is used to assess vertical jump height by measuring the difference between the fully extended standing reach height and the maximal vertical jump and reach height. The reach height for the Vertec was established using a body position of an erect stance, both feet together and flat on the ground, both arms fully extended overhead, and with the head and eyes in a neutral position. The subjects were instructed to perform a countermovement jump (CMJ) that required participants to begin in an upright position with the feet parallel to each other and hip to shoulder width apart. Upon a verbal cue from trained investigators, subjects performed a rapid countermovement by flexing the knees and hips. After the subjects attained their chosen depth of descent, they explosively extended at the hips, knees, and ankles to achieve a maximal jump height at the highest peg they could touch. After the initial description of the CMJ, subjects were provided 2 warm-up jumps. Study participants then completed 3 maximal effort jumps with a 1-minute rest period between each jump attempt. The best of 3 trials was recorded.

Statistical Analyses

Using the SPSS 20.0 statistical software package (SPSS Inc., Chicago, IL, USA), 2-way mixed factorial ANOVA (group × time) with repeated measures on time were used to determine main and interaction effects on all measured dependent variables. When a significant group × time interaction was obtained for any dependent variable, the statistical model was assessed by examining the simple main effects with separate within-group repeated-measures ANOVA and appropriate *t*-tests for each time point.

Test-retest reliability of our testing methods was completed in 3 participants ($n = 3$). Using these data, intraclass correlation coefficients were computed for average power ($r = 0.949$, 95% confidence interval [CI]: 0.593–0.999), peak power ($r = 0.988$, 95% CI: 0.884–0.999), average velocity ($r = 0.880$, 95% CI: 0.280–0.997), and peak velocity ($r = 0.970$, 95% CI: 0.733–0.999). We have included this section in the Statistical Analysis section of our manuscript.

For all analyses, an alpha level of 0.05 was used to determine statistical differences between group mean values. When the sphericity assumption was not met, the Huynh–Feldt correction factor was applied to the entire model. Normality was confirmed using visual inspection of standardized skewness and kurtosis scores and Shapiro-Wilk tests. Sample size was determined a priori using an average effect size of 1.56, alpha level of 0.05, and power ($1 - \beta$) of 0.8 from previously published data (15). All data are presented as mean ± *SD*. For data collected using the TENDO power analyzer, collected values were averaged and recorded as the average of the 3 completed sets for peak power, average power, and peak velocity. For the soreness data, separate 2 × 5 (week × time) mixed factorial ANOVAs were completed individually by group. When a significant group × time interaction effect was found, paired *t*-tests were used to determine statistical significance between each respective time point.

RESULTS

Demographics and Dietary Information

Baseline data for age, height (in centimeters), weight (in kilograms), body composition (fat %), and standing reach (in centimeters), training experience (years), training frequency (days per week), 1RM (in kilograms), and all dietary data (energy, carbohydrates, protein, and fats) are all presented in Table 1. As determined using 1-way ANOVA, no significant differences ($p > 0.05$) at baseline were found for all variables, with the exception of absolute (grams per day) protein intake ($p = 0.03$). Tukey's post hoc tests revealed that the 4S group (214 ± 70 g) consumed significantly more protein than the 2S group (133 ± 44 g, $p = 0.02$) but not the 6S group (166 ± 68 g, $p = 0.20$). Forty participants were randomized into the study, but 10 participants failed to complete the investigation because of noncompliance; thus, all

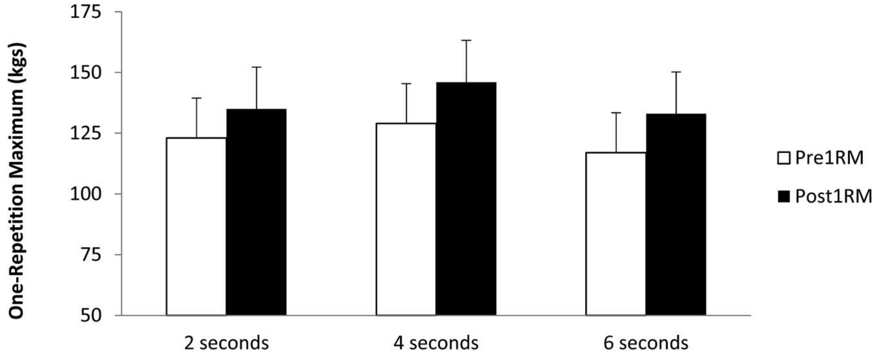

Figure 1. Pretraining and posttraining values for 1 repetition maximum (in kilograms) for all groups. Data are presented as mean ± *SD*. $n = 30$.

Table 3. One repetition maximum, vertical jump, peak power, peak velocity, and average power values.*

		Week 0 (pre)			Week 4 (post)			Significance			
Variable	Group	Set 1	Set 2	Set 3	Set 1	Set 2	Set 3				
1 RM (kg)	2S	124 ± 20	†	†	135 ± 23	†	†	Within	0.007	Time	<0.001
	4S	129 ± 22	†	†	146 ± 30	†	†	Within	<0.001	G × T	0.31
	6S	118 ± 17	†	†	133 ± 17	†	†	Within	<0.001		
Vertical jump (inches)	2S	66 ± 11	†	†	69 ± 11	†	†	Within	0.02	Time	0.004
	4S	69 ± 9	†	†	70 ± 9	†	†	Within	0.40	G × T	0.07
	6S	61 ± 9	†	†	62 ± 9	†	†	Within	0.30		
Peak power (W)	2S	935 ± 184	944 ± 177	941 ± 175	1,023 ± 189	1,051 ± 200	1,062 ± 197	Within	0.001	Time	<0.001
	4S	971 ± 199	1,004 ± 199	1,012 ± 202	1,055 ± 193	1,086 ± 203	1,093 ± 211	Within	0.003	G × T	0.65
	6S	861 ± 117	870 ± 123	870 ± 127	938 ± 134	957 ± 144	961 ± 151	Within	<0.001		
Peak velocity ($m \cdot s^{-1}$)	2S	1.70 ± 0.15	1.72 ± 0.13	1.72 ± 0.13	1.72 ± 0.15	1.76 ± 0.17	1.78 ± 0.17	Within	0.19	Time	0.29
	4S	1.67 ± 0.09	1.73 ± 0.11	1.74 ± 0.09	1.64 ± 0.09	1.69 ± 0.07	1.70 ± 0.08	Within	0.29	G × T	0.04
	6S	1.65 ± 0.15	1.67 ± 0.12	1.67 ± 0.14	1.59 ± 0.12	1.61 ± 0.14	1.62 ± 0.14	Within	0.03		
Average power (W)	2S	528 ± 104	532 ± 103	533 ± 103	576 ± 95	592 ± 108	595 ± 110	Within	0.001	Time	<0.001
	4S	568 ± 127	582 ± 123	579 ± 127	612 ± 116	629 ± 119	630 ± 126	Within	0.002	G × T	0.43
	6S	497 ± 89	499 ± 82	498 ± 84	530 ± 94	538 ± 97	539 ± 99	Within	0.004		

*G = group; T = time.
†Indicates no values.

these data were removed from analysis. Therefore, a remaining total of 30 subjects completed the study, including all familiarization and pretesting sessions, all eccentric training bouts, and all posttesting sessions, with no subjects missing any training sessions. In addition, no injuries or major adverse events occurred for any participant throughout the entire intervention. Training progressions for all workouts, sets, reps, and % load over the 4-week training period are presented in Table 2.

One Repetition Maximum

The group × time interaction effect for 1RM was not statistically significant ($p = 0.31$). There was a significant time effect ($p < 0.001$) for 1RM strength as the 2S (week 0: 124 ± 20 kg vs. week 4: 135 ± 23 kg, $p = 0.007$), 4S (week 0: 129 ± 22 kg vs. week 4: 146 ± 30 kg, $p < 0.001$), and 6S groups (week 0: 118 ± 17 kg vs. week 4: 133 ± 17 kg, $p < 0.001$) all experienced significant increases in maximal strength (Figure 1).

Vertical Jump

The group × time interaction effect for vertical jump did not reach significance but there was a trend toward a difference ($p = 0.07$) and a significant main effect for time was found ($p = 0.004$). Within group analysis of each eccentric duration group revealed that the 2S group (week 0: 66 ± 11 cm vs. week 4: 69 ± 11 cm, $p = 0.02$) reached statistical significance, whereas both the 4S group (week 0: 69 ± 9 cm vs. week 4: 70 ± 9 cm, $p = 0.40$) and the 6S group (week 0: 61 ± 9 cm vs. week 4: 62 ± 9 cm, $p = 0.30$) did not (Table 3).

Peak Power, Mean Power, and Peak Velocity

Peak power, mean power, and peak velocity values from all 3 completed sets were first averaged before statistical analysis using a 2-way mixed factorial (group × time) ANOVA. No group × time interaction effect for peak power was determined ($p = 0.65$). A significant main effect of time ($p < 0.001$) for peak power was found, with each group experiencing a statistically significant increase ($p < 0.005$) across the 4-week eccentric training program. A significant group × time interaction effect was found for changes in peak velocity ($p = 0.04$) with no overall main effect for time ($p = 0.29$). Follow-up within-group analysis revealed that the 2S ($p = 0.19$) and 4S ($p = 0.29$) groups did not experience statistically significant changes in peak velocity, whereas the 6S group did experience a statistically significant reduction ($p = 0.03$) in peak velocity when performing the jump squat protocol. Average power values also revealed no significant group × time interaction ($p = 0.43$). Again, a significant main effect over time was found ($p < 0.001$), indicating that all groups experienced a significant increase in average power production throughout the jump squat protocol. Within-group analysis over time revealed that all 3 groups experienced significant ($p < 0.005$) increases in average power production.

Soreness

At week 0 and week 4, all groups (2S, 4S, and 6S) experienced significant within-group increases ($p \leq 0.05$) in self-reported soreness values. As seen in Figure 2, the 2S group reported a significant ($p = 0.002$) group × time interaction effect between week 0 and week 4 soreness values. Separate paired t-tests at each respective time point (preexercise, postexercise, 24 hours postexercise, 48 hours postexercise, and 72 hours postexercise) revealed significant differences ($p \leq 0.05$) between week 0 and week 4 at the following time points: postexercise ($p = 0.03$), 24 hours postexercise ($p = 0.01$), 48 hours postexercise ($p = 0.01$), and 72 hours postexercise ($p = 0.04$). As seen in Figure 3, the 4S group reported a significant ($p < 0.001$) group × time interaction effect between week 0 and week 4 soreness values. Separate paired t-tests at each respective time point (pre, post, 24 hours post, 48 hours post, and 72 hours post) revealed significant differences ($p \leq 0.05$) between the week 0 and week 4 at the following time points: 24 hours postexercise ($p = 0.01$), 48 hours postexercise ($p = 0.01$), and 72 hours postexercise ($p = 0.04$). Finally, as seen in Figure 4, the

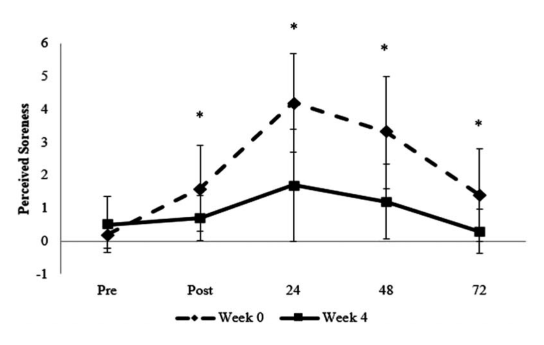

Figure 2. Perceived soreness levels for the 2S (2-second) group from week 0 to week 4. Data are presented as mean ± SD. $n = 10$; "*" indicates that week 4 is significantly different than week 0 at designated time point, $p \leq 0.05$.

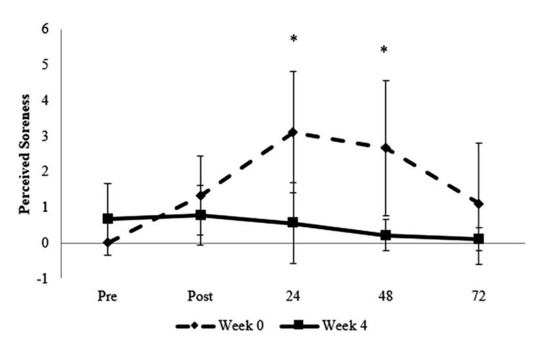

Figure 3. Perceived soreness levels for the 4S (4-second) group from week 0 to week 4. Data are presented as mean ± SD. $n = 9$; "*" indicates that week 4 is significantly different than week 0 at designated time point, $p \leq 0.05$.

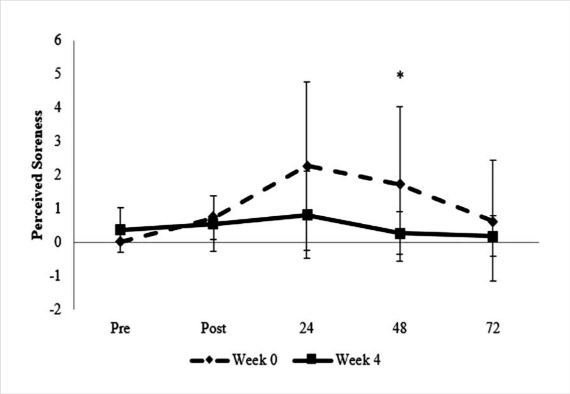

Figure 4. Perceived soreness levels for the 6S (6-second) group from week 0 to week 4. Data are presented as mean ± *SD*. $n = 11$; "*" indicates that week 4 is significantly different than week 0 at designated time point, $p \leq 0.05$.

6S group reported a significant ($p = 0.034$) group × time interaction effect between week 0 and week 4 soreness values. Separate paired *t*-tests at each respective time point (preexercise, postexercise, 24 hours postexercise, 48 hours postexercise, and 72 hours postexercise) revealed significant differences ($p \leq 0.05$) between week 0 and week 4 at the following time points: 48 hours postexercise ($p = 0.046$).

DISCUSSION

The primary findings of this study indicate that a 4-week training period consisting primarily of eccentric contractions of varying durations can significantly increase maximal strength and vertical jump as well as peak and average power production throughout a jump squat protocol. This is the first study to investigate the effects of different durations of eccentric contractions on these variables. When looking closely at the impact of contraction speed, most work has centered upon the entire eccentric-concentric contraction of varying speeds with little to no work focused upon the specific impact of altering the contraction speed and duration of only part of the contraction cycle (concentric only or eccentric only). Considering previous research has demonstrated positive outcomes of eccentric exercise training, this topic permitted examination of the role of different eccentric contraction durations and its impact on exercise performance.

Our maximal strength data revealed that although no interaction was found to indicate one specific eccentric duration group (2S, 4S, or 6S) against the other, all eccentric contraction durations did significantly increase 1RM by 8.9–13.2% over the 4-week training period. Although no other data exist that has specifically manipulated the eccentric contraction speed using a floor-based exercise, other researchers have used open kinetic chain movements in conjunction with an isokinetic dynamometer (23,32). Previous work using eccentric resistance training has incorporated submaximal, maximal (100% 1RM), or supramaximal (typically 105–120% 1RM) training loads to stimulate greater increases in maximal muscle strength in traditional activities involving both concentric and eccentric actions (22,25,26,33,41) compared with conventional types of strength training (10) or using very light loads (5). In comparison to this previous work, results from the present study are in line with these outcomes. It is important to highlight that the present study used a load assignment of 80–85% 1RM and thus was not maximal. It is our contention that this is a meaningful practical find, particularly when we report positive improvements in maximal strength, vertical jump, and power production (Table 3).

Our work supports the results from a number of previous studies that show increases in power as a result of eccentric exercise training (43,44). Optimal power production serves as an important part in nearly all aspects of sports and is critical throughout various parts of the stretch-shortening cycle (SSC) (49). Optimal power production has been shown to be an effective modality in increasing (explosive) muscle strength and muscle cross-sectional area, leading to increased sarcomere length (6,11,17,22,49). From a power perspective, findings from our data reveal a significant increase in vertical jump in the 2S group but not in the 4S or 6S group, and significant increases in all 3 groups for both peak power and average power. The load and volume used to assess power output from our jump squat protocol was 45% 1RM, a value that has been previously shown to align with optimal power production (30). In support of the chosen load, for traditional resistance exercises, Siegel et al. (46) reported maximal power output with loads of 50–70% of 1RM for the squat and 40–60% of 1RM for the bench press. Similarly, studies by Cormie et al. (12–14) found that the optimal loads were 0% of 1RM for the jump squat, 56% of 1RM for the squat, and most recently 40% for jump squats (30).

Peak velocity was the only variable to highlight a significant group × time interaction effect ($p = 0.04$), and it was interesting to find that no changes occurred for peak velocity in the 2S and 4S groups, but peak velocity actually decreased in the 6S group after the 4-week training program (Table 3). In a similar respect, our reported changes in vertical jump approached statistical significance for the group × time interaction ($p = 0.07$), and upon a closer look, only the 2S group experienced a statistically significant improvement in their vertical jump performance, whereas both the 4S and the 6S groups experienced nonsignificant improvements in vertical jump (Table 3). Furthermore, earlier work by Enoka (18) reported that the increased forces associated with eccentric contractions are because of specific activation strategies used by the nervous system, whereas numerous mechanisms of enhanced force production and neural control have been recently proposed in eccentric muscle contractions (16,21). With respect to eccentric training and power output, recent investigations by Cook et al. (11) used 3 weeks of eccentric training combined with over speed exercises in trained athletes and found that the eccentric training block resulted in greater improvements in CMJ peak power when compared with traditional training. Similar results were also shown by Sheppard et al. (43), who investigated jump training exercises 3 times per week for 5 weeks on high-performance male and female volleyball players. Additional loads were applied during the eccentric but not concentric phase of CMJ exercises. In total, both intervention and control groups performed 190 jumps within the 5-week training period, in addition to other strength training exercises. The eccentric accentuated training group improved jump performance by 11%, whereas there was no effect (2%) in the control group. Although these previous reports provide support for the overall changes we found, data are lacking that clearly point toward the different patterns of eccentric contraction duration as what was prescribed in the present study.

Interestingly, the 6-second eccentric group experienced a significant reduction in peak velocity during the jump squat, whereas the 2-second and 4-second groups did not. We speculate this may be manifested by a greater time under tension experienced by the muscle contractile apparatus throughout the training sessions. Although time under tension is considered a primary mechanism for changes in overall muscle hypertrophy, the increased work generated by the musculoskeletal system during eccentric muscle contractions, especially at longer durations, may not be optimal when trying to enhance peak velocity and greater concentric speeds of contraction. During an eccentric contraction, muscle absorbs energy developed by an external load. Therefore, during an eccentric muscle action, the shock absorber-spring-component of the muscle tendon system contributes energy to the forces produced. In this regard, another proposed mechanistic explanation of the reduction in peak velocity in the 6-second group entails that of the SSC. Although the SSC is considered an important component in muscle force generation and eccentric activity (49), and because of the time component function during the SSC, it could be that the coupling time between the eccentric and concentric phase during SSC from the longer eccentric duration may have been too long. Specifically, any elastic energy was lost as heat, thereby not being able to contribute to force generating capacity.

Furthermore, the 2-second group experienced an increase in vertical jump height, whereas the 4-second and 6-second groups did not. We associate this to the principle of specificity as subjects in the 2-second group and those who may participate in explosive types of activities often experience similar patterns of eccentric contraction time needed for a specific movement. As previously mentioned, Sheppard et al. (43) investigated jump training exercises 3 times per week for 5 weeks on high-performance male and female volleyball players. Additional loads were applied during the eccentric but not concentric phase of CMJ exercises. Overall, both intervention and control groups performed 190 jumps during the 5-week training period, in addition to other strength training exercises. The eccentric accentuated training group improved jump performance by 11%, whereas there was no change in the control group.

Certainly, a coach or athlete may view the changes for each group relative to vertical jump or peak velocity production as an unfavorable outcome, but these results are not surprising when considering the specificity principle of exercise training. Although no data are available that perfectly aligns with our work, other outcomes can help in better understanding these outcomes. For example, recently, Wirth et al. (53) analyzed the effects of an eccentric strength training protocol using supramaximal loads on different maximal and explosive strength parameters of the lower extremity and tested eccentric maximal strength, maximal isometric strength (MVC), 1RM, explosive strength (RFD), CMJ, and squat jump before and after 6 weeks of training. The training group composed of 15 individuals with limited weight training experience and a control group of 13 subjects, also with limited weight training experience. The lower body was trained 3 days per week using a 45° leg press. Each training session comprised 5 sets of 3 repetitions with a 6-minute rest between each set. After 6 weeks, a significant increase in eccentric max strength (28.2%) and 1RM (31.1%) were found in the experimental group who trained with supramaximal loads. The increases observed in the control group showed nonsignificant changes. Although the changes in MVC, RFD, and vertical jump heights were not significantly different in both groups, unlike in our present study, it does shed more light on potential outcomes of these training variables with respect to eccentric training.

In light of these findings, one might want to be cognizant of this potential outcome with respect to vertical jump and peak velocity and program design. Similarly, for those interested in increasing vertical jump, coaches and athletes need to be aware of the possible impact of longer contraction durations and their potential ability to make the muscle slower. Certainly, for some sports or positions this might be favorable, regardless, this is an important consideration and one that needs future research to provide more information. In this respect, our work is the first study to examine the effects of eccentric contraction durations that include vertical jump and power output measures. Although numerous training methods and programs are used to enhance vertical jump and power output, we encourage strength and conditioning coaches and fitness professionals to use aspects of eccentric contraction durations throughout the yearly training cycle to further promote aspects of sports performance and to further understand how manipulating the eccentric component can go on to impact strength, power, and vertical jump performance.

Strengths of our study design center mostly upon the practical considerations to strength and conditioning and fitness professionals as we completed this investigation. As such, our chosen eccentric load, although lighter than maximal and supramaximal eccentric techniques commonly used (29), accomplished a few important outcomes. First, all our participants got stronger, jumped higher, and produced more power (Table 3). Second, the loading program we used (4 × 6 reps @ 80–85% 1RM) could serve as an excellent guide for a coach or trainer who wants to prescribe eccentric work. Third, this load allowed for a single athlete to complete nearly all repetitions on their own without help or a spot (2-second group), with the exception of some repetitions toward the latter part of sets, particularly in the 4S and 6S groups. This is an important consideration for a coach who may have previously used maximal eccentric work that would require multiple spotters and would allow much more time to complete a single set and a complete workout. Another strength of our workout was that every repetition was directly supervised and strictly monitored for appropriate squatting technique and compliance to the prescribed contraction duration. Although limited data existed to guide us as to how to program our workouts, we feel that a single workout consisting of a 2-, 4-, or 6-second duration while completing 4 sets of 6 repetitions at a load of 80–85% 1RM could serve as an optimal starting point for most athletes and coaches. Overall, this is an important consideration for strength and conditioning professionals who choose to implement eccentric contraction durations into their programs, as using either a 2-, 4-, or 6-second eccentric duration is likely to initiate favorable adaptations from a strength and power perspective.

There were some limitations to this study that deserve attention. Our data are best extrapolated to young, healthy, and previously trained males. Although this population is arguably the most likely to use eccentric training, other populations such as older individuals, females, rehabilitation patients, and other clinical populations may or may not respond in the same manner as our study cohort. Second, our chosen measure of muscle strength was the barbell Smith squat exercise. We recognize that some individuals may perceive this as a less practical exercise and may not extrapolate well to other sports-related activities. However, we would like to emphasize that in the attempt to incorporate eccentric training, we prioritized the use of a closed kinetic chain movement that engaged multiple joints across the lower body in a movement pattern that has practical application to sport performance as opposed to a single-joint, open kinetic chain movement that has been used in previous studies (19,23). We recognize that using a movement such as the free bar back (or front) squat might be preferred by many, but these lifts using this type of training could invoke greater levels of physical risk that we felt were not justified. This is particularly important when considering that limited data exist to document whether controlled manipulation of eccentric contraction duration would instigate favorable resistance training adaptations. For these reasons, we chose the Smith squat exercise to limit potential injury and to have greater control over technique. Third, our measured changes of strength, power measures, and soreness were limited only to the measurement times outlined in this protocol. Although the current study was limited to 4 weeks of training, strength and conditioning professionals can prescribe 2-, 4-, or 6-second eccentric durations for any part of the yearly training cycles, and especially during off-season play to further promote increases in strength, power, and hypertrophy.

An interesting note to share with readers is that although all groups performed the same amount of volume over the course of the study (4 × 6 reps) and while a metronome was used by trained investigators to ensure all prescribed contraction duration parameters were followed, the chosen percent range (80–85% 1RM) required load adjustments for many in the 4S and 6S groups because subjects were unable to complete the necessary sets and reps for their prescribed eccentric duration. Specifically, many participants in the 4S group and all participants in the 6S group required a load reduction of 10% in order for all remaining repetitions and sets to be completed at the revised resistance level and at the same contraction duration. This adjustment was made at the start of the first workout to allow all subjects to complete the first workout, and most commonly at the beginning of workout #5 after re-establishment of the subject's 1RM. Although this reduction and load adjustment may not pose a limitation per se, it is our contention that when prescribing eccentric contraction durations for 4 and 6 seconds, we suggest strength and conditioning and fitness professionals take a more conservative approach for loading parameters (i.e., 65–70% 1RM) in order for their athletes and clients to adhere to the prescribed contraction duration for a given training session, particularly if they are choosing to use a 4- or 6-second contraction duration. Furthermore, it is important for strength and conditioning and fitness professionals to recognize these findings to allow future investigations to explore any acute manipulation of training variables and how they may impact overall changes in performance, particularly with volume and even rest periods. As an example, we chose to follow NSCA guidelines for rest with strength-related loading patterns, and reducing the rest interval would have made it extremely challenging for the study participants in the longer eccentric durations (4S and especially 6S) to complete a program with a similar volume and intensity. Finally, some strength and conditioning coaches might prefer to use a forced repetition approach with spotters as opposed to stopping the set and adjusting the load as was completed in the present study. Although this approach brings in subtle differences, we feel the differences are minor and that many athletes would respond positively to either approach (stopping and adjusting load vs. completing forced repetitions with spotters). Notably and from a practical perspective, using forced repetition would likely be more time efficient, an attribute likely of great interest to a strength and conditioning coach.

Previous work by Seger and Thorstensson (42) examined the effects of eccentric vs. concentric training on thigh muscle strength and electromyography (EMG). Two groups of young healthy adult men performed 10 weeks of either eccentric or concentric unilateral isokinetic knee extensor training at 90°, 4 sets of 10 maximal efforts, 3 days a week. Changes in strength of the trained legs revealed more signs of specificity related to velocity and contraction type after eccentric when compared with concentric training. No major training effects were present when observing eccentric to concentric ratios of agonist EMG activity or in relative antagonist (hamstring) activation. Thus, for the trained leg, the muscle action type and speed-specific changes in maximal voluntary eccentric strength could not be related to any effects on neural mechanisms, such as a selective increase in muscle activation during eccentric actions. Although both types of training elicited cross-education effects, that is, action type and velocity, specific increases in strength occurred in the contralateral untrained leg, accompanied by a specific increase in eccentric to concentric EMG ratio after eccentric training. Similar results were also recently reported by Carvalho et al. (7). Although a number of differences exist between our work and these data, it does provide an indication that capturing such information as part of training programs may be helpful. Nonetheless, it could have provided a deeper look into the skeletal muscle response to the eccentric manipulation of our training program, and as a result, it is recommended that future investigations use such approaches.

In conclusion, results from a 4-week resistance training program involving the Smith squat exercise that emphasized eccentric contractions of varying duration showed significant increases in maximal strength, vertical jump, peak and average power, and peak velocity. All study participants tolerated the exercise program well, and consequently, coaches and athletes are encouraged to look at the parameters of our work and program their own eccentric programs in an attempt to achieve similar outcomes. Although much more research is needed to better understand how to best prescribe and program eccentric exercise, results from the present study are an appropriate first step.

PRACTICAL APPLICATIONS

In recent years, the interest level of strength and conditioning professionals in the incorporation of varying levels of eccentric exercises has increased. In light of this interest, the present study was designed to provide data using a floor-based (closed kinetic chain), multi-joint movement at assigned loads that an athlete could safely complete on their own with a single spotter. For these reasons, we feel that strength and conditioning professionals who develop programs with the intention to increase muscle strength and power output from eccentric muscular contractions will find a number of important conclusions from this study. Eccentric muscular contractions require greater work and effort on the musculoskeletal system throughout a given range of motion and for any given exercise. From this consideration alone, coaches and strength and conditioning professionals should be cognizant of the overall readiness level of an athlete and determine to what extent an athlete may be able to complete such training. Even in the face of our relatively short training program and incorporation of just 1 exercise, our data provide outcomes suggestive of favorable adaptations to strength, power, velocity, and vertical jump in all groups. In this respect, these data are the first to demonstrate to coaches and athletes how altering the duration of eccentric contraction can impact and how an athlete is able to adapt from a strength and power perspective. Moreover, results from our work also inform coaches of how to prescribe eccentric activity as part of a greater training cycle. In this respect, our findings inform strength and conditioning coaches and fitness professionals how to better understand the expressions of strength and power in response to changing durations of eccentric activity. Most importantly, these data can inform training programming and show how a group of young, healthy males with previous resistance training experience are able to respond. Further to this point, we contend that a load of 80–85% 1RM at an assigned work output of 4 × 6 reps operates as a reasonable "upper limit" of what an athlete can handle on their own and successfully (and safely) complete the workout. Many of our subjects required that we reduce the load throughout some point of the workout in the 4S and 6S groups, but the 2S group responded without a need for a load change. Finally, our soreness data provide indications for coaches on how to potentially assign an eccentric workout to effectively minimize soreness and muscle damage. Finally, additional well-controlled eccentric training studies on trained populations are needed using similar movement patterns and different movement patterns (upper vs. lower) to expand the understanding of the underlying mechanisms that impact strength and power expression and development.

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