Changes in the Eccentric Phase Contribute to Improved Stretch–Shorten Cycle Performance after Training

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ABSTRACT

CORMIE, P., M. R. McGUIGAN, and R. U. NEWTON. Changes in the Eccentric Phase Contribute to Improved Stretch–Shorten Cycle Performance after Training. *Med. Sci. Sports Exerc.*, Vol. 42, No. 9, pp. 1731–1744, 2010. **Purpose**: To determine whether ballistic power training and strength training result in specific changes in stretch–shorten cycle (SSC) function during the eccentric (ECC) phase and, if so, whether these changes are influenced by the individual's strength level. **Methods**: Thirty-two male subjects were divided into four groups: stronger power training group (SP, n = 8, squat one-repetition maximum–to–body mass ratio (1RM/BM) = 1.97 ± 0.08), weaker power training group (WP, n = 8, 1RM/BM = 1.32 ± 0.14), weaker strength training group (WS, n = 8, 1RM/BM = 1.28 ± 0.17), or control group (C, n = 8, 1RM/BM = 1.37 ± 0.13). Training involved three sessions per week for 10 wk. The SP and WP groups performed maximal-effort jump squats with 0%–30% 1RM, and the WS group performed back squats at 75%–90% 1RM. Maximal strength, jump performance, musculotendinous stiffness, and neural activation were assessed before training and after 5 and 10 wk of training. **Results**: Both power and strength training elicited significant changes in a multitude of ECC variables that were significantly associated with improvements in concentric (CON) performance. Enhancements in CON performance were theorized to be driven by the development of a strategy to better use the ECC phase during jumping (i.e., greater unloading allowed for increased negative acceleration and thus velocity during the countermovement and improved musculotendinous stiffness resulted in an enhanced ability to translate the momentum developed during the ECC phase into force). Although a significant improvement in maximal strength resulted in changes to SSC function during the ECC phase, the initial strength level did not significantly affect the ECC variables before training or the magnitude of adaptations in individuals exposed to ballistic power training. **Conclusions**: Training-induced alterations in SSC function during the ECC phase contributes to improvements in jump performance after both ballistic power training and heavy strength training. **Key Words:** STRETCH–SHORTEN CYCLE, STIFFNESS, NEUROMUSCULAR ADAPTATIONS, POWER, STRENGTH

Muscle function required in athletic movements rarely calls for the use of eccentric (ECC) or concentric (CON) muscle actions in isolation. However, the successive combination of ECC and CON muscle actions form the most common type of muscle function required in athletic movements, that is, the stretch–shorten cycle (SSC). When a muscle fiber is activated, stretched, then immediately shortened (i.e., SSC), the muscular force and power generated during the CON action are greater than those achievable by a CON-only contraction (5). As a result, maximal muscular power is superior in movements involving an SSC (1,2,5,16,24,39). Although there is a consensus within the literature regarding the potentiating effect of an SSC on performance, the mechanisms responsible for improved performance during SSC movements are an issue of debate among researchers.

The ECC phase–induced improvement in subsequent CON muscular function has been theorized to be due to several factors including the following: 1) the time available to develop force and thus a higher "preload" at the initiation of the CON phase, 2) interaction effects between the contractile and elastic elements, 3) potentiation of contractile elements, 4) storage and utilization of elastic energy, and 5) activation of stretch reflexes (1,3,5,16,24,37,39). Arguably, the primary mechanism driving the superior maximal power output observed during SSC movements is based on the fact that it takes time for the muscle to generate force (due to time constraints imposed by stimulation, excitation, and contraction dynamics [38]) and for that force to be transmitted to the skeleton (stretch of the muscle–tendon unit [MTU]). The ECC action during a SSC movement allows time for the agonist muscles to develop considerable force and for the system to stiffen

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before the CON contraction. In contrast, the CON contraction starts as soon as force development (beyond that which is required to maintain a static position) begins in CON-only movements. Hence, force during the CON phase (specifically early in the CON phase) is greater than that in SSC movements; thus, impulse is higher, subsequently resulting in superior performance (1,37,39). The interaction effect between the contractile and elastic elements is another mechanism believed to contribute considerably to SSC-induced improvement in maximal power production (15,16). Higher force at the beginning of the CON phase during SSC movements results in greater tendinous lengthening with less fascicle lengthening (23,26,27). As the CON contraction progresses, the muscle fiber contracts at a nearly constant length (i.e., quasi-isometric), whereas the rapid shortening of the MTU largely depends on the shortening of the tendinous structure (i.e., tendon recoil) (23,26,27). In contrast, although some tendinous displacement does occur, most of the MTU length changes during CON-only movements are due to fascicle shortening (23). The minimal displacement of muscle fibers during SSC movements means that they operate closer to their optimal length and, on the basis of the length–tension relationship, can therefore produce more force (26,27). Furthermore, although the net shortening velocity of the MTU is high, fascicle length change occurs at relatively slow velocities during SSC movements, and thus, fascicles are able to generate high forces according to the force–velocity relationship (19). The potentiation of the contractile machinery (i.e., actin–myosin cross bridges) is another mechanism thought to contribute to the SSC-induced enhancement in maximal power output (5,9,15,39). In tetanized isolated muscle and single muscle fibers, an active stretch has been observed to enhance work output of the contractile machinery during subsequent shortening (5,6). These *in vitro* findings have been supported by *in vivo* studies involving intact muscle–tendon complexes (5,9,39). This potentiating effect is thought to be due to enhanced force production per cross bridge rather than an increase in the number of active cross bridges (6). Another mechanism believed to contribute to the SSC-induced enhancement of maximal power is the storage and utilization of elastic energy (4,5). When an active MTU is stretched, mechanical work is absorbed by the MTU, and this work can be stored in part as potential energy in the series elastic component (includes fiber cross bridges, aponeurosis, and tendon) (4,5). It is believed that some of this potential energy can then be used to increase the mechanical energy and positive work during the following CON contraction (2,4,5,24). This recoil of the series elastic component is thought to contribute to the increased force at the beginning of the CON phase in SSC movements and, ultimately, to enhanced performance (2,4,5,24). A further mechanism proposed to contribute to the enhanced CON performance during SSC movements is the activation of spinal reflexes. The forced lengthening of the MTU during the ECC phase of SSC movements causes a mechanical deformation of the muscle spindles that activate reflex mechanisms (30). The stretch reflex subsequently increases muscle stimulation, resulting in increased contraction force during the CON phase and ultimately contributes to enhanced maximal power output (3,36). The extent to which each of these factors influences the performance of SSC movements has been shown to be dependent on the rate and magnitude of the stretch (5,9,16) as well as on the time constraints applied to the movement (5). Thus, the contribution of these mechanisms and their ability to enhance CON performance during SSC movements are heavily dependent on the conditions involved with the ECC phase.

The beneficial effects of strength (22,40), ballistic power (13,29,40), as well as plyometric (21,40) training on power production during the CON phase have been well documented. However, to date, no conclusive evidence exists identifying how the aforementioned mechanisms contributing to enhanced SSC performance are affected by training. One of several speculative theories suggests that increasing strength through training would allow for the athlete to generate more force at the beginning of the CON phase and thus positively affect maximal power in SSC movements (25). Similarly, training-induced increases in neural drive would also allow for increased force production throughout a SSC movement and contribute to improving SSC performance (34). In addition, changes to the pattern of neural activation have been observed after plyometric training so that muscles are activated earlier during the SSC movement (7,34). Another theory suggests that disinhibition occurs in response to plyometric training, potentially leading to the development of greater musculotendinous stiffness (34). The increased activation earlier in the movement and reduction of inhibition effects could potentially influence the force at the start of the CON phase as well as augment the interaction effects of the contractile and elastic elements and the storage and utilization of elastic energy by promoting length change in the tendinous structures rather than the fascicles. In addition, the increased activation could perhaps enhance contractile potentiation by increasing the number of active cross bridges present during the stretch. Further research is required to explore these speculative theories and identify the mechanisms driving training-induced improvements in SSC performance. Specifically, it is not known how any mode of resistance training impacts power, force, or velocity during the ECC phase of sports-specific SSC movements. This is surprising considering the importance of the ECC phase to SSC function and highlights a deficiency in our understanding of the mechanisms driving improved performance after training.

It has been well established that the utilization of an SSC results in more powerful movements (1–3,5,24,28) and that the enhancement of power during the CON phase is largely dependent on the conditions involved with the ECC muscle action (i.e., rate and magnitude of stretch and time of movement) (5,9). Extensive investigation has focused on how CON phase variables (i.e., power, force, velocity, or displacement) respond to various training interventions (13,21,22,29,40). However, there is a distinct lack of research that reports the impact of resistance training on the ECC phase variables of SSC movements. This limits the ability of previous research to elucidate if training causes specific alterations in SSC function, and if so, how such alterations contribute to training-induced improvements in performance. Consequently, it is not known if training-induced changes in CON performance are driven by changes during the ECC phase. Therefore, the purpose of this experiment was to determine whether ballistic power training and heavy strength training result in specific changes in SSC function during the ECC phase and, if so, whether these changes are influenced by the individual's strength level.

METHODS

Experimental design. This study used a randomized, control design. Subjects were divided into two strata on the basis of their squat one-repetition maximum–to–body mass ratio (1RM/BM)—stronger or weaker. Subjects in the stronger stratum were allocated into the stronger power training group (SP, n = 8, 1RM/BM = 1.97 ± 0.08). Subjects in the weaker stratum were randomized into one of three groups: weaker power training group (WP, n = 8, 1RM/BM = 1.32 ± 0.14), weaker strength training group (WS, n = 8, 1RM/BM = 1.28 ± 0.17), or control group (C, n = 8, 1RM/BM = 1.37 ± 0.13). The three training groups completed 10 wk of experimental training, whereas subjects in the C group maintained their normal level of activity. Training involved three sessions per week in which subjects performed heavy back squats (strength training) or maximal-effort jump squats (power training). Subjects completed a 2-d testing battery before initiating training (baseline), after 5 wk of training (midtest—experimental training groups only), and after the completion of 10 wk of training (posttest). Subjects were adequately familiarized to all testing procedures before the actual assessment. The testing protocol involved assessment of maximal strength, jump performance, musculotendinous stiffness, and neural activation.

Subjects. Male subjects who could perform a back squat with proficient technique were recruited for this study. A total of 45 men fulfilled all the testing and training requirements of this investigation. Data from 13 of these men were removed from analysis on the basis of their 1RM/BM ratio to establish two strata with very distinct differences in maximal strength (i.e., classifications were defined as follows: stronger, 1RM/BM > 1.85; weaker, 1RM/BM < 1.50). Data from the remaining 32 men meeting the stronger and weaker classifications were used for this study (age = 23.4 ± 4.4 yr, height = 179.3 ± 6.7 cm, mass = 79.6 ± 12.0 kg). Subject characteristics for each group throughout the duration of the study are outlined in Table 1. The participants were notified about the potential risks involved and gave their written informed consent. This study was approved by the university's human research ethics committee.

Training programs. Both power (SP and WP) and strength (WS) training programs involved three sessions per week each separated by at least 24 h of recovery. Subjects refrained from any additional lower body resistance training, plyometrics, or sprint training outside the experimental training throughout the course of the study. Each power training session was initiated via a warm-up consisting of two sets of six submaximal-effort jump squats with 0% 1RM (i.e., countermovement jumps with no external load, just the resistance applied by a carbon fiber pole (mass = 0.4 kg) held across the shoulders). During sessions 1 and 3 of each week, subjects performed seven sets of six maximal-effort jump squats separated by a 3-min recovery. Jump squats were performed at the load that maximized power output for each individual subject, as determined during the baseline testing session. Similar to previous research, a load consistent with the subject's BM (i.e., no external load or 0% 1RM) maximized power output

TABLE 1. Subject characteristics of the experimental and C throughout the 10 wk of training.

	BM (kg)	Body Fat (%)	1RM/BM	Jump Height (m)
SP group				
Baseline	79.1 ± 12.8	12.2 ± 3.9 ϴ	1.97 ± 0.08 †	0.43 ± 0.03 ‡
Mid-Test	79.8 ± 12.9	12.3 ± 3.8 ϴ	1.93 ± 0.11 ‡	0.50 ± 0.03*Φ
Post-Test	79.6 ± 13.0	12.6 ± 3.5 ϴ	1.88 ± 0.11 †	0.50 ± 0.03*Φ§
WP group				
Baseline	79.9 ± 14.5	17.3 ± 3.8	1.32 ± 0.14	0.38 ± 0.04
Mid-Test	79.2 ± 14.2	17.5 ± 4.0	1.38 ± 0.16	0.42 ± 0.07
Post-Test	79.1 ± 13.8	17.7 ± 3.6	1.39 ± 0.17	0.44 ± 0.06
WS group				
Baseline	82.2 ± 13.7	16.7 ± 4.6	1.28 ± 0.17	0.39 ± 0.04
Mid-Test	82.8 ± 13.6	16.0 ± 4.6	1.57 ± 0.14*ϴ	0.42 ± 0.03
Post-Test	83.3 ± 12.7	15.9 ± 4.4	1.64 ± 0.13*ϴ§	0.43 ± 0.04
C group				
Baseline	77.5 ± 8.1	14.6 ± 3.5	1.37 ± 0.13	0.41 ± 0.04
Post-Test	78.4 ± 8.8	14.7 ± 3.8	1.35 ± 0.12	0.40 ± 0.04

* Significantly ($P \leq 0.05$) different from baseline.
† Significant ($P \leq 0.05$) difference between SP and all other groups.
‡ Significant ($P \leq 0.05$) difference between SP and both WP and WS groups.
§ Significantly ($P \leq 0.05$) different from C group.
ϴ Significant ($P \leq 0.05$) difference between WP and WS groups.
Φ Significant ($P \leq 0.05$) difference between SP and WS groups.

for each of the participants in this study (13,14). The second training session of each week included an additional warm-up set consisting of five submaximal-effort jump squats with 30% 1RM. Subjects then performed five sets of five maximal-effort jump squats with 30% 1RM separated by a 3-min recovery. The intensity was modified for each session so that subjects could hear an audible beep during jumps that reached 95% of the maximal power output at that load from their previous training or testing session. Previous literature has shown significant performance improvements after jump squat training with similar programming parameters at both 0% 1RM (13) and 30% 1RM (29,40). The strength training group followed a daily undulating program involving the back squat exercise exclusively. Each of the sessions was initiated with a warm-up consisting of 10 repetitions with an unloaded barbell (20 kg), 6 repetitions with 50% of that session's working resistance, and 4 repetitions with 70% of that session's working resistance. Adequate recovery was permitted between each warm-up set (3 min). Session 1 of the week involved three sets of three repetitions at 90% 1RM. Session 2 involved three sets of six repetitions at 75% 1RM. Session 3 involved three sets of four repetitions at 80% 1RM. All sessions involved an interset rest period of 5 min. These intensities were based on baseline 1RM values for the first 5 wk of training and midtest 1RM values for the last 5 wk of training. The load was reduced by 5% 1RM for the remainder of the session if subjects were unable to complete the required number of repetitions or were unable to reach a knee angle of less than 90° of flexion during the lift. If subjects completed each of the required repetitions with ease (i.e., the subjects perceived that they could have successfully completed an additional repetition), the load was increased by 5% during that particular session the following week. Subjects were encouraged to perform the CON phase of each squat as rapidly as possible while maintaining correct technique. Previous literature has shown significant improvements in maximal strength of relatively untrained participants after training with similar programming parameters (33).

Testing protocol. Subjects had 3–5 d of recovery between their previous training session and the midtest testing session. A period of 7–10 d of rest was required between the final training session and the posttest testing session to allow full recovery. The testing session was initiated with the assessment of maximal dynamic strength using a back squat 1RM to a depth consistent with a knee angle of at least 90° of flexion. During a 30-min recovery, body composition was assessed using dual-energy x-ray absorptiometry (DEXA, Discovery A; Hologic, Inc, Bedford, MA). Body composition was assessed using the standard DEXA three-compartment model (bone, lean tissue, and fat tissue), and whole-body percent fat was defined as the ratio of fat mass to total mass. Maximal isometric strength was then evaluated using an isometric squat test (to assess maximal voluntary muscle activation). Adequate recovery was permitted (10 min) before examination of jump squat performance across a series of intensities: 0% (i.e., no external load or BM only), 20%, 40%, 60%, and 80% of squat 1RM. Static jump performance was also assessed at 0% 1RM. Subjects completed the jump conditions in a randomized order that was consistent across the three testing occasions for each individual subject. Kinematic, kinetic, and EMG data were obtained simultaneously throughout the testing session.

Data acquisition and analysis procedures. The back squat 1RM involved subjects completing a series of warm-up sets (four to six repetitions at 30% estimated 1RM, three to four repetitions at 50% estimated 1RM, two to three repetitions at 70% estimated 1RM, and one to two repetitions at 90% estimated 1RM) each separated by 3 min of recovery. A series of maximal lift attempts (no more than five) were then performed until a 1RM was obtained. This protocol has been frequently reported throughout the previous literature for the assessment of maximal dynamic strength (13,14,29). Only trials in which subjects reached a knee angle of less than 90° of flexion were considered successful. This depth was visually monitored during testing and confirmed by two-dimensional motion analysis (SP: baseline = 85.7° ± 4.2°, posttest = 82.5° ± 6.8°; WP: baseline = 83.4° ± 2.4°, posttest = 80.4° ± 4.3°; WS: baseline = 86.0° ± 5.4°, posttest = 84.7° ± 3.7°; C: baseline = 83.1° ± 6.2°, posttest = 82.6° ± 5.4°; rater reliability: $r = 0.95$). The isometric squat test was performed with subjects standing on a force plate (9290AD; Kistler Instruments, Winterthur, Switzerland) in a back squat position pushing against an immovable rigid bar. Subjects were instructed to perform a rapid, maximal effort to reach maximal force output as soon as possible and maintain that force for 3 s. Performance of a jump squat involved subjects completing a maximal-effort countermovement jump while holding a rigid bar across their shoulders. Subjects held a 0.4-kg carbon fiber pole for the 0% 1RM jump squat, whereas for all other intensities, subjects held a 20-kg barbell loaded with the appropriate weight plates. Participants were instructed to keep constant downward pressure on the bar throughout the jump and were encouraged to move the resistance as fast as possible to achieve maximal power output with each trial. Performance of the static jump also involved subjects holding the 0.4-kg carbon fiber pole across their shoulders. Subjects were instructed to lower into a back squat position with a knee angle of approximately 90° of flexion and hold this position for 3 s. When instructed, subjects then jumped as rapidly as possible in an attempt to maximize power output while performing no previous countermovement. Trials with any kind of countermovement, determined as any degree of unloading in the vertical ground reaction force–time curve immediately before the jump, were repeated. The bar was not to leave the shoulders of the subject, with the trial being repeated if this requirement was not met. A minimum of two trials at each load were completed, with additional trials performed if peak power and jump height were not within 5% of the previous jump squat. Adequate rest was enforced between all trials (3 min).

All jump squats were performed while the subject was standing on a force plate (9290AD; Kistler Instruments) with a linear position transducer (LPT; PT5A-150; Celesco Transducer Products, Chatsworth, CA) attached to the bar. The LPT was attached 10 cm to the left of the center of the bar to avoid any interference caused by movement of the head during the jump. The LPT was mounted above the subject, and the retraction tension of the LPT (equivalent to 8 N) was accounted for in all calculations. Analog signals from the force plate and LPT were collected for every trial at 1000 Hz using a data acquisition system including analog-to-digital card (cDAQ-9172; National Instruments, North Ryde, NSW, Australia). Custom programs designed using LabVIEW software (Version 8.2; National Instruments) were used for recording and analyzing the data. Signals from the force plate and LPT were filtered using a fourth-order, low-pass Butterworth digital filter with cutoff frequencies of 50 and 10 Hz, respectively. From laboratory calibrations, the force plate and LPT voltage outputs were converted into vertical ground reaction force and displacement, respectively. The vertical velocity of the movement was determined using a first-order derivative of the displacement data. Power output was calculated as the product of the vertical velocity and vertical ground reaction force data. Acceleration of the movement was calculated using a second-order derivative of the displacement data and was smoothed using a fourth-order, low-pass Butterworth digital filter with a cutoff frequency of 10 Hz. This data collection and analysis methodology has been validated previously (11), and test–retest reliability for all jump variables examined was consistently $r \geq 0.90$.

A series of performance variables were assessed during the jump squats. Variables were assessed in both the ECC and CON phases, which were defined as follows: ECC phase, from the initiation of the countermovement (i.e., initial change in velocity) to minimum displacement (i.e., zero velocity); CON phase, from 0.001 s (i.e., next sample) after minimum displacement/zero velocity to take off (i.e., when force output first reached zero). Peak ECC and CON values were evaluated as the maximum positive or negative value achieved during the respective phases. Average ECC force and power were calculated from the beginning to the end of the ECC phase of the jump squat. Average CON force and power were calculated from the beginning of the CON phase to the time at which peak force or power occurred. The ratio between average ECC power and average CON power was also determined and termed the power ratio. Rate of force development (RFD) was determined between the minimum and maximum force during the ECC phase. Total RFD was assessed between the minimum and maximum force that occurred throughout the movement. Net impulse was assessed as the integral of vertical ground reaction force over the period of application in which force exceeded that required during stationary standing (i.e., above BM). Time to take off was determined as the time between the initiation of the countermovement (i.e., start of the ECC phase) and the point that force was first zero (i.e., end of the CON phase—take off). In addition, musculotendinous stiffness of the lower body was estimated during the 0% 1RM jump squat using a simple spring–mass model consisting of a mass (representing the center of mass of the system) and a single linear leg spring (which connected the feet to the center of mass) (31). Stiffness was defined as the ratio of the peak vertical force in the spring at the end of the ECC phase to the vertical displacement of the spring at the moment when it is maximally compressed (i.e., by dividing vertical ground reaction force at the end of the ECC phase by the change in vertical displacement during the ECC phase of the jump) (17).

In addition to these instantaneous performance variables, analyses of parameters throughout the jump movement were conducted. The force–time and velocity–time curves from each individual subject were selected from the beginning of the ECC phase to the end of the CON phase. Using a custom-designed LabVIEW program, the number of samples in each individual curve was then modified to equal 500 samples by changing the time delta (dt) between samples and resampling the signal (dt = number of samples in the original signal/500). The sampling frequency of the normalized signals was calculated according to the following equation:

$$\begin{array}{c}\text{Normalized sampling}\\ \text{frequency (Hz)}\end{array} = \frac{1\ \text{s}}{\left[\frac{\text{(no. samples in original signal)}}{\text{(no. samples in normalized signal)}}\right] \times \left[\begin{array}{c}\text{seconds}\\ \text{per sample}\end{array}\right]}$$

Consequently, the sampling frequency of the modified signals was then equivalent to 776 ± 148 Hz for the force–time and velocity–time curves. This resampling allowed for each individual force and velocity curve to be expressed during equal periods of time (i.e., the 500 samples represented the relative time—from 0% to 100%—taken to complete the jump). In other words, the various data sets were normalized to total movement time so that data could be pooled. Each sample of the normalized force–time and velocity–time curves was then averaged across subjects within the SP, WP, WS, or C groups, resulting in averaged curves with high resolution (sampling frequency of 776 Hz). The normalized force–time and velocity–time curves were used to create force–velocity loops by plotting the instantaneous force (y-axis) and velocity (x-axis) at each time point (i.e., 0%–100% of the time from the beginning of the ECC phase to the end of the CON phase). Because velocity is plotted on the x-axis, the force–velocity loops allow for a clear delineation between the ECC (i.e., negative velocity or area on left of the y-axis) and CON (i.e., positive velocity or area on the right of the y-axis) phases. Intraclass test–retest reliability for force–time and velocity–time curves during the jump squat has consistently been $r \geq 0.90$ and $r \geq 0.89$ using this methodology (12).

EMG of the vastus lateralis (VL), vastus medialis (VM), and biceps femoris (BF) was collected on the dominate leg during the isometric squat and all jump squats. Disposable

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surface electrodes (self-adhesive Ag/AgCl snap electrode, 2-cm interelectrode distance, 1-cm circular conductive area (Product 272; Noraxon USA, Inc., Scottsdale, AZ)) were attached to the skin over the belly of each measured muscle, distal to the motor point, and parallel to the direction of muscle fibers. A reference electrode was placed on the patella. The exact location of the electrodes relative to anatomical landmarks was marked on a sheet of tracing paper following the first testing session to ensure consistent placement in subsequent tests. Each site was shaved, gently abraded, and cleansed with alcohol before electrode placement to minimize skin impedance. Raw EMG signals were collected at 1000 Hz and amplified (gain = 1000, bandwidth frequency = 10–1000 Hz, input impedance < 5 kΩ (Model 12D-16-OS Neurodata Amplifier System; Grass Technologies, West Warwick, RI)). The amplified myoelectric signal was collected simultaneously with force plate and LPT data using a data acquisition system including an analog-to-digital card, and custom programs designed using LabVIEW software were used for recording and analyzing the data. The signal was full wave rectified and filtered using a dual-pass, sixth-order, 10- to 250-Hz band-pass Butterworth filter as well as a notch filter at 50 Hz. A linear envelope was created using a low-pass, fourth-order Butterworth digital filter with a cutoff frequency of 6 Hz. Maximal voluntary contraction (MVC) for all muscles was determined by averaging the integrated EMG signal during a 1-s period of sustained maximal force output after the initial peak in the force curve during the isometric squat (intraclass test–retest reliability consistently $r \geq 0.91$). EMG activity during jumping was analyzed by averaging the integrated EMG signal during the (a) full jump, (b) ECC phase, and (c) CON phase. To standardize for time, the average integrated EMG (AvgIEMG) values were then divided by the respective time of each of these phases (i.e., time to take off, time of ECC phase, and time of CON phase, respectively). The AvgIEMG value for each phase was then normalized by expressing it relative to the MVC. This is similar to methods previously used when comparing EMG between movements with different time components (32). Intraclass test–retest reliability for all EMG variables examined was consistently $r \geq 0.80$.

Statistical analyses. A general linear model with repeated-measures ANOVA followed by Bonferroni *post hoc* tests was used to examine the impact of training on performance variables and to determine whether differences existed between the groups at baseline, midtest, and posttest. Statistical significance for all analyses was defined by $P \leq 0.05$, and results were summarized as means ± SD. Estimated effect sizes (ES) of $\eta^2 = 0.473$, $\eta^2 = 0.911$, and $\eta^2 = 0.394$ at the observed power levels of 0.908, 1.000, and 0.802 for average ECC power after training existed for SP, WP, and WS, respectively. Estimated ES of $\eta^2 = 0.648$, $\eta^2 = 0.653$, and $\eta^2 = 0.480$ at observed power levels of 0.997, 0.997, and 0.916 for average CON power after training existed for SP, WP, and WS, respectively. In addition, comparisons between the experimental groups after training revealed estimated ES of $\eta^2 = 0.141$ and $\eta^2 = 0.639$ at observed power levels of 0.321 and 0.999 for average ECC and CON power, respectively. Relationships between the training-induced changes in a series of variables were calculated using the Pearson correlation coefficient (r). The strength of the correlation coefficient was determined on the basis of the classifications outlined by Cohen (8) where $r = 0.10$–0.29 has a small effect, $r = 0.30$–0.49 has a moderate effect, and $r \geq 0.5$ has a large effect. Mean ES was also calculated to examine and compare the practical significance of the differences among the experimental groups and training-induced changes. Based on Cohen (8), which suggests that ES of 0.2, 0.5, and 0.8 represent a small, moderate, and large effect, practical relevance was defined as an ES ≥ 0.8 for the purpose of this study.

RESULTS

Maximal strength. The SP group had significantly greater 1RM/BM than all other groups at each of the testing occasions (Table 1). After training, no significant changes to 1RM/BM were observed for SP, WP, or C groups. The stronger group did, however, display a practically relevant decrease in 1RM/BM at posttest (ES = 0.93; equivalent to a 7 ± 7-kg decrease in 1RM). The strength training program resulted in significant improvements in 1RM/BM in the WS group at both midtest and posttest. These improvements resulted in significant differences in 1RM/BM between WS and WP at both midtest and posttest as well as between WS and WP at posttest (Table 1).

Jump performance. A variety of significant changes in the ECC phase variables were observed in each of the training groups after training (Tables 2–4 and Fig. 1). Furthermore, the change in these ECC variables between baseline and posttest was significantly correlated with the change in a variety of CON performance variables after training (Table 5). The power training groups significantly enhanced CON performance in SSC movements (i.e., jump squats), but no such improvement was observed in the CON-only movement (i.e., static jump). In contrast, the WS group significantly improved CON performance in both the SSC and CON-only jumps (Tables 2 and 3). Before training, no between-group differences in ECC phase variables existed between the groups; however, after training, several significant differences between the groups were observed (Tables 2 and 3).

Force–velocity loop. Training-induced changes to the force–velocity loop (i.e., significant improvement in both force and velocity) during the 0% 1RM resulted in significant improvements during the following phases: (a) SP, 41.0%–51.8% and 82.8%–100.0% of normalized time (Fig. 2A); (b) WP, 17.2%–50.0% and 64.2%–79.2% of normalized time (Fig. 2B); and (c) WS, 31.6%–56.8% of normalized time (Fig. 2C). No significant changes were observed in the force–velocity loop of the C group (Fig. 2D).

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TABLE 2. ECC and CON performance variables during the 0% 1RM jump squat (i.e., unloaded countermovement jump).

	SP Group			WP Group			WS Group			C Group	
0% 1RM Jump Squat	Baseline	Midtest	Posttest	Baseline	Midtest	Posttest	Baseline	Midtest	Posttest	Baseline	Posttest
Peak ECC power ($W \cdot kg^{-1}$)	−25.6 ± 10.9	−43.9 ± 7.3*‡	−50.0 ± 8.3*Φ§	−15.9 ± 3.7	−34.2 ± 5.7*	−40.7 ± 6.4*§	−18.3 ± 10.1	−26.6 ± 9.7	−34.3 ± 10.5*§	−23.4 ± 10.7	−22.0 ± 8.6
Average ECC power ($W \cdot kg^{-1}$)	−10.9 ± 2.9	−15.3 ± 1.8*Φ	−15.2 ± 1.8*§	−8.1 ± 1.3	−13.8 ± 1.9*	−14.8 ± 0.9*§	−8.7 ± 3.5	−11.7 ± 2.9	−13.5 ± 2.8*§	−10.0 ± 3.8	−9.9 ± 2.7
Peak CON power ($W \cdot kg^{-1}$)	59.1 ± 3.9‡	68.8 ± 6.3*	68.5 ± 2.9*Φ§	51.2 ± 6.1	58.3 ± 9.8	60.3 ± 8.5	50.2 ± 5.2	56.9 ± 6.0	59.1 ± 7.4*	53.6 ± 5.2	53.7 ± 5.7
Average CON power ($W \cdot kg^{-1}$)	32.3 ± 4.0‡	39.5 ± 4.9*	41.3 ± 3.0*†	25.9 ± 3.2	32.9 ± 4.3*	34.4 ± 3.5*§	25.7 ± 3.6	30.1 ± 3.2*	31.9 ± 3.3*§	28.1 ± 3.3	27.4 ± 3.3
Peak ECC force ($N \cdot kg^{-1}$)	22.6 ± 4.0	27.6 ± 5.7‡	30.6 ± 4.8†	17.9 ± 2.2	23.1 ± 3.5*	25.0 ± 4.5*§	16.5 ± 2.1	20.0 ± 2.9*	20.8 ± 1.6*	19.1 ± 3.2	18.7 ± 2.8
Average ECC force ($N \cdot kg^{-1}$)	9.9 ± 0.6	10.8 ± 0.9	11.4 ± 0.8*Φ§	9.5 ± 0.3	10.4 ± 0.5	10.8 ± 0.9§	9.5 ± 0.5	9.9 ± 0.6	10.1 ± 0.4	9.7 ± 0.7	9.7 ± 0.2
Minimum force ($N \cdot kg^{-1}$)	2.7 ± 1.7	0.8 ± 0.5*	0.7 ± 0.7*§	4.9 ± 1.8	1.2 ± 0.9*	0.6 ± 0.4*§	3.9 ± 2.6	2.6 ± 2.0	1.6 ± 2.4	2.9 ± 2.6	3.0 ± 2.4
Force at start of CON ($N \cdot kg^{-1}$)	22.4 ± 4.1‡	26.9 ± 5.9Φ	30.1 ± 4.4*†	17.8 ± 2.2	22.7 ± 3.5*	24.5 ± 3.9*§	16.5 ± 2.0	19.8 ± 2.7*	20.6 ± 1.4*	18.9 ± 3.1	18.4 ± 2.6
Peak CON force ($N \cdot kg^{-1}$)	23.9 ± 3.5‡	27.7 ± 5.2‡	30.4 ± 4.3*†	19.8 ± 2.0	23.3 ± 36	24.5 ± 3.9*§	19.6 ± 1.8	21.5 ± 1.6	21.4 ± 1.5	20.5 ± 2.4	20.2 ± 2.2
Average CON force ($N \cdot kg^{-1}$)	22.5 ± 3.8‡	26.3 ± 4.4‡	29.0 ± 4.4*†	18.2 ± 2.0	21.8 ± 3.4	22.3 ± 3.0*	17.9 ± 1.6	19.8 ± 1.8	20.2 ± 1.3	19.2 ± 2.7	18.4 ± 2.4
Total RFD ($N \cdot kg^{-1} \cdot s^{-1}$)	60.6 ± 28.6‡	126.2 ± 54.8*Φ	147.7 ± 62.3*Φ§	25.6 ± 9.4	80.9 ± 35.2	120.2 ± 80.2*§	29.0 ± 12.5	51.3 ± 30.7	52.1 ± 18.8	40.0 ± 25.3	38.3 ± 22.5
ECC RFD ($N \cdot kg^{-1} \cdot s^{-1}$)	68.0 ± 30.1‡	130.3 ± 49.6*‡	152.9 ± 58.4*Φ§	28.6 ± 10.3	85.4 ± 32.2	120.3 ± 80.2*§	31.6 ± 16.8	56.7 ± 29.6	78.0 ± 48.7*	45.8 ± 27.0	42.5 ± 23.8
Peak ECC velocity ($m \cdot s^{-1}$)	−1.80 ± 0.50	−2.15 ± 0.14	−2.14 ± 0.21§	−1.74 ± 0.34	−2.02 ± 0.20	−2.12 ± 0.24*§	−1.71 ± 0.39	−1.87 ± 0.21	−2.07 ± 0.27	−1.78 ± 0.36	−1.78 ± 0.28
Peak CON velocity ($m \cdot s^{-1}$)	3.11 ± 0.26	3.44 ± 0.32	3.46 ± 0.17*§	2.89 ± 0.15	3.23 ± 0.41	3.44 ± 0.31*§	2.88 ± 0.29	3.11 ± 0.30	3.26 ± 0.30*	3.01 ± 0.23	3.05 ± 0.23
Peak ECC displacement (m)	−0.42 ± 0.12	−0.38 ± 0.07	−0.35 ± 0.07§	−0.46 ± 0.1	−0.44 ± 0.1	−0.43 ± 0.1	−0.48 ± 0.13	−0.47 ± 0.10	−0.48 ± 0.12	−0.47 ± 0.08	−0.49 ± 0.08
Peak CON displacement (m)	0.44 ± 0.04‡	0.48 ± 0.05	0.50 ± 0.03*Φ§	0.38 ± 0.04	0.42 ± 0.07	0.44 ± 0.06	0.39 ± 0.04	0.42 ± 0.03	0.43 ± 0.04	0.41 ± 0.04	0.40 ± 0.04

* Significantly ($P \leq 0.05$) different from baseline.
† Significant ($P \leq 0.05$) difference between SP and all other groups.
‡ Significant ($P \leq 0.05$) difference between SP and both WP and WS groups.
§ Significantly ($P \leq 0.05$) different from C group.
Φ Significant ($P \leq 0.05$) difference between SP and WS groups.

TABLE 3. CON performance variables during the 0% 1RM static jump (i.e., CON-only jump).

	SP Group			WP Group			WS Group			C Group	
0% 1RM Static Jump	Baseline	Midtest	Posttest	Baseline	Midtest	Posttest	Baseline	Midtest	Posttest	Baseline	Posttest
Peak CON power ($W \cdot kg^{-1}$)	55.0 ± 4.8‡	58.2 ± 6.6	59.5 ± 5.9x§	45.4 ± 5.7	49.2 ± 8.7	49.2 ± 8.0	44.8 ± 6.1	47.8 ± 6.1	54.2 ± 7.9*	48.5 ± 5.2	48.1 ± 5.1
Average CON power ($W \cdot kg^{-1}$)	22.8 ± 2.8†	23.1 ± 5.5	25.6 ± 2.3x§	17.6 ± 2.5	20.1 ± 3.9	19.9 ± 3.7	17.3 ± 1.9	20.6 ± 2.4	24.9 ± 3.3*Θ§	19.3 ± 2.4	18.7 ± 3.3
Force at start of CON ($N \cdot kg^{-1}$)	12.7 ± 0.9	11.7 ± 1.6	13.8 ± 2.7	11.8 ± 1.8	12.9 ± 2.1	12.6 ± 2.5	11.3 ± 0.9	12.9 ± 2.0	13.8 ± 2.7	12.0 ± 0.9	11.7 ± 1.3
Peak CON force ($N \cdot kg^{-1}$)	23.8 ± 1.8Φ§	25.0 ± 2.0‡	25.4 ± 1.5†	20.9 ± 3.2	22.2 ± 2.5	23.0 ± 2.3§	19.5 ± 1.9	21.2 ± 1.0	21.9 ± 1.3*	20.4 ± 1.1	20.2 ± 1.3
Average CON force ($N \cdot kg^{-1}$)	18.3 ± 1.0†	18.8 ± 2.3	20.4 ± 2.1§	16.3 ± 1.6	18.1 ± 2.1	18.4 ± 2.2§	15.3 ± 1.0	17.6 ± 1.8	19.0 ± 1.2*§	16.1 ± 1.0	15.8 ± 1.1
Total RFD ($N \cdot kg^{-1} \cdot s^{-1}$)	67.3 ± 22.7Φ§	84.7 ± 34.3‡	89.6 ± 21.7Φ§	42.7 ± 26.6	52.5 ± 15.8	66.2 ± 21.9§	31.6 ± 9.3	44.8 ± 12.6	47.5 ± 11.9*	36.5 ± 7.3	35.3 ± 8.4
Peak CON velocity ($m \cdot s^{-1}$)	2.92 ± 0.28§	3.00 ± 0.26	3.12 ± 0.17	2.66 ± 0.22	2.73 ± 0.27	2.82 ± 0.34	2.49 ± 0.22	2.67 ± 0.23	2.91 ± 0.35	2.66 ± 0.25	2.73 ± 0.26
Peak CON displacement (m)	0.39 ± 0.06Φ	0.41 ± 0.06	0.42 ± 0.04§	0.33 ± 0.05	0.34 ± 0.07	0.35 ± 0.07	0.31 ± 0.03	0.35 ± 0.04	0.37 ± 0.05*	0.34 ± 0.04	0.34 ± 0.04

* Significantly ($P \leq 0.05$) different from baseline.
† Significant ($P \leq 0.05$) difference between SP and all other groups.
‡ Significant ($P \leq 0.05$) difference between SP and both WP and WS.
§ Significantly ($P \leq 0.05$) different from C.
Θ Significant ($P \leq 0.05$) difference between WP and WS.
x Significant ($P \leq 0.05$) difference between SP and WP
Φ Significant ($P \leq 0.05$) difference between SP and WS.

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TABLE 4. Average power during the ECC and CON phases of the static jump (i.e., CON-only) and jump squat (i.e., countermovement) across a range of loads. The power ratio (i.e., ratio between ECC and CON average power) is also displayed.

		SP Group			WP Group			WS Group			C Group	
Jump	Phase	Baseline	Midtest	Posttest	Baseline	Midtest	Posttest	Baseline	Midtest	Posttest	Baseline	Posttest
0% 1RM static	CON (W·kg^{-1})	22.8 ± 2.8†	23.1 ± 5.5	25.6 ± 2.3¤§	17.6 ± 2.5	20.1 ± 3.9	19.9 ± 3.7	17.3 ± 1.9	20.6 ± 2.4*	23.9 ± 3.6*§	19.3 ± 2.4	18.7 ± 3.3
0% 1RM jump squat	ECC (W·kg^{-1})	−10.5 ± 2.9	−14.1 ± 2.7*Φ	−14.9 ± 1.5*§	−8.4 ± 2.1	−13.6 ± 1.9*	−14.9 ± 1.1*§	−8.4 ± 3.5	−11.0 ± 3.1	−12.7 ± 3.6*§	−9.7 ± 3.8	−9.5 ± 2.5
	CON (W·kg^{-1})	32.3 ± 4.0‡	39.5 ± 4.9*‡	41.3 ± 3.0*†	25.9 ± 3.2	32.9 ± 4.3*	34.4 ± 3.5*§	25.7 ± 3.6	30.1 ± 3.2*	31.9 ± 3.3*§	28.1 ± 3.3	27.4 ± 3.3
	Power Ratio	0.31 ± 0.06	0.38 ± 0.05*	0.38 ± 0.05*	0.32 ± 0.07	0.42 ± 0.06*	0.44 ± 0.05*	0.32 ± 0.11	0.36 ± 0.09	0.40 ± 0.10	0.34 ± 0.11	0.35 ± 0.08
20% 1RM jump squat	ECC (W·kg^{-1})	−9.7 ± 2.1	−13.3 ± 1.1*Φ	−13.6 ± 1.3*§	−7.1 ± 1.5	−12.2 ± 2.0*	−13.8 ± 1.9*§	−8.6 ± 2.3	−10.1 ± 2.3	−11.4 ± 2.7*§	−9.2 ± 3.2	−8.6 ± 2.2
	CON (W·kg^{-1})	25.7 ± 2.5‡	29.8 ± 2.0*Φ	31.1 ± 1.6*Φ§	20.8 ± 1.7	27.0 ± 3.5*Θ	29.0 ± 2.6*Θ§	21.8 ± 2.8	23.5 ± 2.1	24.9 ± 2.2*	23.4 ± 3.0	23.1 ± 2.4
	Power Ratio	0.38 ± 0.09	0.45 ± 0.02	0.44 ± 0.04	0.34 ± 0.08	0.45 ± 0.06*	0.48 ± 0.05*§	0.39 ± 0.08	0.43 ± 0.08	0.45 ± 0.08	0.39 ± 0.10	0.37 ± 0.08
40% 1RM jump squat	ECC (W·kg^{-1})	−8.2 ± 2.7	−11.3 ± 0.9*Φ	−12.7 ± 1.4*§	−6.4 ± 2.1	−11.2 ± 1.7*Θ	−12.9 ± 2.5*Θ§	−7.2 ± 2.7	−7.9 ± 3.4	−9.7 ± 2.3	−7.9 ± 2.2	−7.3 ± 2.4
	CON (W·kg^{-1})	22.1 ± 3.2‡	24.9 ± 2.7Φ	27.5 ± 1.8*Φ§	17.7 ± 3.0	23.9 ± 3.7*Θ	25.8 ± 2.8*Θ§	17.4 ± 3.2	19.3 ± 2.0	21.4 ± 2.1*	20.2 ± 2.3	19.6 ± 1.8
	Power Ratio	0.37 ± 0.11	0.46 ± 0.03*	0.46 ± 0.06*	0.36 ± 0.12	0.47 ± 0.06*	0.50 ± 0.09*§	0.41 ± 0.12	0.41 ± 0.17	0.45 ± 0.08	0.39 ± 0.10	0.37 ± 0.10
60% 1RM jump squat	ECC (W·kg^{-1})	−6.5 ± 2.7	−8.7 ± 3.3	−9.0 ± 2.3	−6.2 ± 2.2	−9.2 ± 2.3	−9.9 ± 3.4*	−6.2 ± 2.7	−6.6 ± 2.5	−9.3 ± 1.9*	−6.8 ± 3.1	−6.7 ± 3.2
	CON (W·kg^{-1})	17.1 ± 3.5	19.1 ± 5.4	21.3 ± 3.5 §	15.2 ± 3.3	18.8 ± 3.2	21.0 ± 2.7*§	14.5 ± 3.0	15.6 ± 2.5	18.2 ± 2.3*	17.4 ± 2.5	16.5 ± 1.4
	Power Ratio	0.37 ± 0.09	0.46 ± 0.11	0.42 ± 0.06	0.42 ± 0.16	0.49 ± 0.10	0.47 ± 0.12	0.43 ± 0.17	0.44 ± 0.17	0.51 ± 0.06	0.38 ± 0.13	0.39 ± 0.15
80% 1RM jump squat	ECC (W·kg^{-1})	−7.2 ± 1.8	−7.5 ± 3.5	−7.3 ± 2.4	−5.4 ± 1.8	−7.4 ± 2.2	−6.8 ± 2.1	−5.5 ± 2.7	−5.7 ± 2.0	−7.2 ± 1.4	−6.1 ± 1.5	−5.9 ± 1.8
	CON (W·kg^{-1})	15.6 ± 3.6	15.9 ± 6.5	15.8 ± 4.7	11.5 ± 2.9	16.1 ± 4.4	18.0 ± 3.9*§	11.9 ± 3.1	13.5 ± 3.6	14.8 ± 1.6	13.5 ± 2.8	12.9 ± 2.1
	Power Ratio	0.47 ± 0.12	0.46 ± 0.07	0.46 ± 0.09	0.50 ± 0.21	0.46 ± 0.08	0.37 ± 0.06	0.46 ± 0.16	0.45 ± 0.18	0.49 ± 0.09	0.47 ± 0.18	0.46 ± 0.13

* ($P \leq 0.05$) different from baseline.
† Significant ($P \leq 0.05$) difference between SP and all other groups.
‡ Significant ($P \leq 0.05$) difference between SP and both WP and WS groups.
§ Significantly ($P \leq 0.05$) different from C group.
Φ Significant ($P \leq 0.05$) difference between SP and WS groups.
Θ Significant ($P \leq 0.05$) difference between WP and WS groups.
¤ Significant ($P \leq 0.05$) difference between SP and WP groups.

Comparison of the force–velocity loop between the groups revealed no significant differences throughout the 0% 1RM jump squat at baseline or midtest occasion (Figs. 3A and B). At posttest, significant differences in the force–velocity loop were evident between the C group and both SP and WP training groups from 42.0% to 77.2% of normalized time (Fig. 3C). Furthermore, significant differences also existed between the SP and C groups at 77.4%–90.8% of normalized time (Fig. 3C).

Musculotendinous stiffness. Stiffness of the lower body was significantly higher than baseline measures at the posttesting occasion for the SP and WS groups (Table 6). No significant within-group changes were observed in the WP and C groups throughout the study (Table 6). The SP group had significantly greater stiffness than the WS group at baseline, midtest, and posttest. In addition, differences between the SP and both WP and C groups at baseline were approaching statistical significance (P = 0.19 and P = 0.11, respectively). Furthermore, the SP group displayed significantly greater stiffness than the C group at posttest (Table 6).

Neural activation. Despite trends toward increased EMG activity during the 0% 1RM jump squat after training, no significant within-group differences were observed in AvgIEMG during the full jump, ECC, or CON phases as well as AvgIEMG at the start of the CON phase (Table 7). No significant differences in EMG activity existed among the SP, WP, WS, and C groups at any of the testing occasions (Table 7).

DISCUSSION

The primary finding of this investigation was that both ballistic power training and heavy strength training elicited significant changes in a multitude of ECC phase variables during SSC movements, which were significantly associated with improvements in CON performance (Tables 1–5 and Figs. 1–3). In addition, although a significant improvement in strength resulted in considerable alterations during the ECC phase, the initial strength level did not significantly affect ECC variables before training or the magnitude of adaptations in individuals exposed to ballistic power training.

Training-induced changes in SSC function. As one of the first experiments to comprehensively examine the training adaptations throughout both the ECC and CON phases of sports-specific SSC movements, the findings of the current study highlight that both ballistic power training and heavy strength training result in significant changes in a variety of ECC phase variables (i.e., peak and average ECC power, peak and average ECC force, minimum force, and peak ECC velocity). Importantly, the significant relationships between the changes in a variety of CON performance variables and changes in the corresponding ECC variables indicate that training-induced alterations in the ECC phase contribute to the improvements in CON performance commonly reported throughout the literature (13,21,22,29,40).

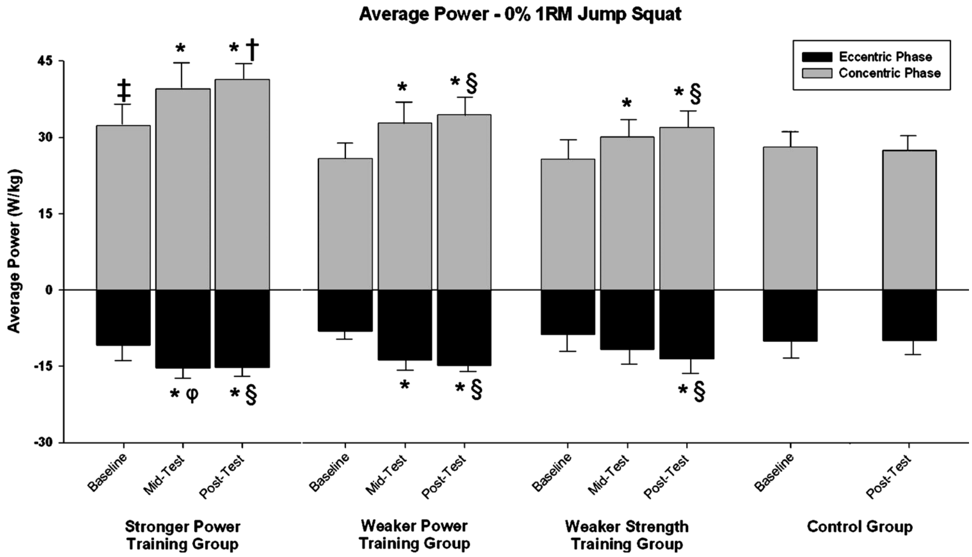

FIGURE 1—Average ECC and CON power during the 0% 1RM jump squat (i.e., BM only) throughout the 10 wk of training. *Significantly ($P \leq 0.05$) different from baseline. †Significant ($P \leq 0.05$) difference between SP and all other groups. ‡Significant ($P \leq 0.05$) difference between SP and both WP and WS groups. ΦSignificant ($P \leq 0.05$) difference between SP and WS groups. §Significantly ($P \leq 0.05$) different from C group.

For example, improvements in peak and average CON power were significantly related to changes in peak and average ECC power after training ($r = -0.71$ and $r = -0.77$, respectively; $n = 32$). These findings offer important insights into the mechanisms driving adaptations in SSC function after both ballistic power training and heavy strength training.

Ballistic power training resulted in significant improvements in CON performance during SSC movements but not CON-only movements (Tables 2 and 3). This suggests that training caused adaptations specific to the ECC phase that formed the basis of improved CON performance during SSC movements. Interestingly, in the 0% 1RM jump squat, the magnitude of change in ECC power exceeded the increase in CON power, which resulted in a significant change in the power ratio (Table 4). Similarly, ECC force and velocity both changed to a greater degree than CON force and velocity after training (Table 2). These results support the suggestion that the adaptations of SSC function after ballistic power training occur primarily in the ECC phase, and these changes form the basis for improved CON performance. The foundation of the observed changes is believed to be associated with specific changes to jumping mechanics. Force throughout the ECC phase changed significantly after training (i.e., minimum force, peak ECC force, average ECC force, and ECC RFD; Table 2 and Fig. 2), but the range of motion during the ECC phase remained unchanged (i.e., peak ECC displacement). Therefore, the stiffness of the system increased, as indicated by the significant change observed in the combined data of both SP and WP groups after training (baseline = 3472 ± 871 N·m, midtest = 5358 ± 2734 N·m ($P = 0.10$), posttest = 6075 ± 2922 N·m ($P = 0.01$)). In addition, when the data of both power training groups are combined, peak ECC velocity significantly increased at both midtest and posttest (baseline = -1.77 ± 0.41 m·s^{-1}, midtest = -2.08 ± 0.18 m·s^{-1} ($P = 0.01$), posttest = -2.13 ± 0.22 m·s^{-1} ($P = 0.00$)). These changes to force and velocity throughout the ECC phase resulted in a significant change in ECC power after training (Table 2 and Figs. 2 and 3). Therefore, the participants developed a strategy to better utilize the ECC phase. Specifically, greater unloading allowed for increased negative acceleration (i.e., utilized acceleration due to gravity to a greater degree). This, in turn, increased peak velocity during the ECC phase. Due to the fact that greater force was developed across the same range of motion during the ECC phase (i.e., no change in peak ECC displacement), the stiffness of the system increased. As a result, subjects were better able to translate the momentum developed into force and therefore increased CON performance (i.e., force, velocity, power, and jump height).

TABLE 5. Relationship between the change (Δ) in a variety of performance measures after 10 wk of training ($n = 32$).

Correlation Between:	*r*	*P*	Effect
Δ Peak ECC and CON power	−0.71	0.00*	Large
Δ Average ECC and CON power	−0.77	0.00*	Large
Δ Peak ECC and CON force	0.89	0.00*	Large
Δ Average ECC and CON force	0.79	0.00*	Large
Δ Peak ECC and total RFD	0.92	0.00*	Large
Δ Peak ECC and CON velocity	−0.50	0.00*	Large
Δ Peak ECC and CON displacement	−0.04	0.85	Trivial
Δ Average ECC power and:			
Δ Peak CON power	−0.65	0.00*	Large
Δ Average CON power	−0.77	0.00*	Large
Δ Peak CON force	−0.04	0.83	Trivial
Δ Average CON force	−0.05	0.79	Trivial
Δ Force at start of CON	−0.30	0.10	Moderate
Δ Total RFD	−0.22	0.24	Small
Δ Peak CON velocity	−0.77	0.00*	Large
Δ Net impulse	−0.78	0.00*	Large
Δ Peak CON displacement	−0.58	0.00*	Large

The statistical significance of the relationship (P value) as well as the strength of the correlations (Effect) on the basis of the classifications outlined by Cohen (8) is displayed.
* Significant ($P \leq 0.05$) correlation.

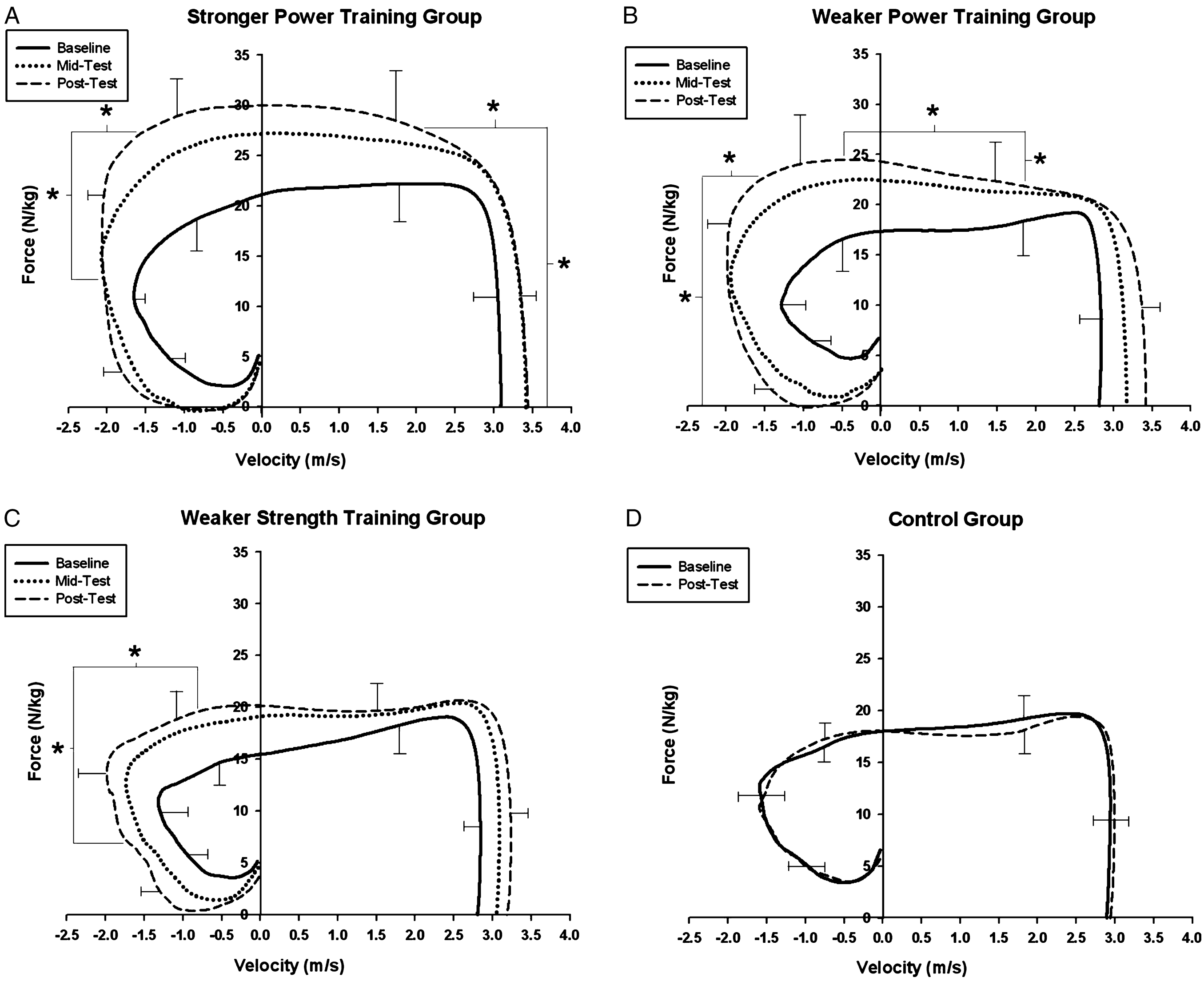

FIGURE 2—Training-induced changes to the force–velocity loop for the 0% 1RM jump squat in SP (A), WP (B), WS (C), and C groups (D). *Significant ($P \leq 0.05$) difference in both force and velocity between baseline and posttest.

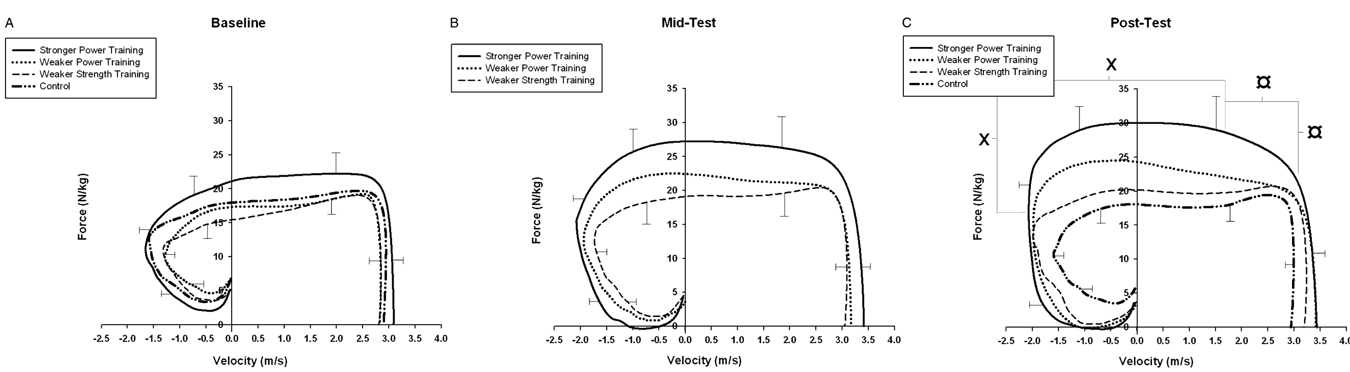

FIGURE 3—Between-group comparisons of the force–velocity loop during the 0% 1RM jump squat at baseline (A), midtest (B), and posttest (C). xSignificant ($P \leq 0.05$) difference in both force and velocity between the C and both SP and WP groups. ¤Significant ($P \leq 0.05$) difference in both force and velocity between the C and SP groups.

TABLE 6. Stiffness of the lower body throughout the 10 wk of training.

	Stiffness (N·m)		
	Baseline	Midtest	Posttest
SP Group	3871 ± 880Φ	6355 ± 3126Φ	7318 ± 3066*Φ§
WP Group	3122 ± 745	4485 ± 2170	4986 ± 2472
WS Group	2603 ± 694	3615 ± 1112	3995 ± 1375*
C Group	3025 ± 556	–	3070 ± 823

* Significantly ($P \leq 0.05$) different from baseline.
§ Significantly ($P \leq 0.05$) different from C group.
Φ Significant ($P \leq 0.05$) difference between SP and WS groups.

The jumping strategy developed following ballistic power training is theorized to have several important implications regarding the potential mechanisms contributing to improved CON performance. First, similar to comparisons between SSC and CON-only movements, the enhanced ability to generate higher force at the beginning of the CON phase following training allowed for greater CON force, velocity, power, and, ultimately, jump height (1,37,39). Second, the greater force developed during the ECC phase, which led to the higher force level at the beginning of the CON phase after training, indicates that greater tendinous lengthening with less fascicle lengthening was likely to occur during the ECC phase (i.e., increased active stiffness regulation) (23,26,27). As the CON contraction progressed, the muscle fibers would then have contracted at a nearly constant length (i.e., quasi-isometric), whereas the rapid shortening of the MTU would have largely depended on the shortening of the tendinous structure (i.e., tendon recoil) (23,26,27). As a result, the minimal displacement of muscle fibers during the SSC movement would mean that they operated closer to their optimal length and, on the basis of the length–tension relationship, could therefore produce more force (26,27). In addition, although the net shortening velocity of the MTU would be high in such situations, fascicle length change would occur at relatively slow velocities. Thus, fascicles would be able to generate higher forces according to the force–velocity relationship (19). Furthermore, elastic energy would be stored predominately in the tendinous structures and, therefore, could be utilized with minimal dissipation via the tendon recoil during the CON phase (20). Third, the increased force production during the ECC phase may positively influence the SSC potentiation of contractile elements. For enhanced force generation during the ECC phase (as observed in the current study), a greater number of active action–myosin cross bridges would be required, thus increasing the potential for contractile potentiation during the stretch (5,9,15,39). Finally, an increased rate of stretch (i.e., peak ECC velocity) has the potential to enhance the storage and utilization of elastic energy as well as the activation of the stretch reflex during SSC movements (5,30), although the contribution of these two factors may be relatively small in maximal ballistic efforts (37). Therefore, the contribution of each of these mechanistic factors to improving CON performance may have been enhanced by the training-induced changes observed during the current study.

Heavy strength training resulted in significant improvements in CON performance during both SSC movements and CON-only movements (Tables 2 and 3). These observations suggest that the contractile capacity of the lower limb musculature was enhanced after strength training. This theory is supported by the existing literature identifying the neuromuscular adaptations commonly elicited by heavy strength training (10,18). Consequently, strength-trained subjects increased the magnitude of RFD and, as a result, were able to accelerate their mass to a greater degree, which, similar to the power training groups, allowed for the generation of greater force during the ECC phase (Table 2 and Figs. 2 and 3). As a result, the force developed at the start of the CON phase was significantly increased, leading to improvements in CON force, velocity, and power after training. In addition, the WS subjects could tolerate higher stretch loads after training as a result of their increased strength level and thus could perform a faster countermovement. This was supported by the increased stiffness and the strong tendency toward increasing

TABLE 7. AvgIEMG during the full 0% 1RM jump squat as well as during the ECC and CON phases.

	SP Group			WP Group			WS Group		
AvgIEMG	Baseline	Midtest	Posttest	Baseline	Midtest	Posttest	Baseline	Midtest	Posttest
VM									
Full jump (% MVC·s^{-1})	114.5 ± 24.2	145.2 ± 25.8	148.0 ± 45.3	108.8 ± 29.0	121.9 ± 52.3	115.3 ± 19.0	102.3 ± 27.1	111.9 ± 40.3	110.7 ± 47.0
ECC phase (% MVC·s^{-1})	74.3 ± 21.9	91.4 ± 17.0	108.3 ± 36.1	80.5 ± 21.1	81.8 ± 37.0	82.2 ± 15.7	80.9 ± 25.9	82.3 ± 33.5	84.1 ± 32.2
CON phase (% MVC·s^{-1})	196.8 ± 53.3	232.4 ± 56.8	226.2 ± 77.9	169.8 ± 57.5	183.9 ± 81.0	173.0 ± 29.1	163.9 ± 45.8	164.3 ± 56.1	164.4 ± 49.0
At start of CON (% MVC)	204.3 ± 56.1	261.2 ± 64.1	261.8 ± 104.9	173.4 ± 80.0	190.4 ± 102.6	193.5 ± 95.1	167.0 ± 56.3	186.1 ± 69.4	174.0 ± 84.9
VL									
Full jump (% MVC·s^{-1})	115.2 ± 28.3	122.3 ± 20.0	135.0 ± 28.5	118.8 ± 46.8	130.1 ± 59.3	106.0 ± 25.7	100.9 ± 15.3	105.2 ± 25.3	105.7 ± 30.4
ECC phase (% MVC·s^{-1})	69.6 ± 17.3	78.1 ± 17.9	90.0 ± 27.5	86.8 ± 37.7	87.3 ± 36.8	88.7 ± 19.3	75.5 ± 17.5	72.6 ± 22.3	74.1 ± 25.9
CON phase (% MVC·s^{-1})	205.7 ± 47.7	206.7 ± 34.9	222.9 ± 52.4	187.9 ± 72.0	187.7 ± 64.3	186.0 ± 74.6	159.7 ± 28.3	167.3 ± 44.3	164.5 ± 47.5
At start of CON (% MVC)	183.0 ± 41.1	208.6 ± 40.0	247.7 ± 117.0	169.0 ± 78.7	188.0 ± 136.6	187.4 ± 101.3	204.1 ± 122.1	202.1 ± 110.5	192.1 ± 51.0
BF									
Full jump (% MVC·s^{-1})	125.6 ± 21.8	195.5 ± 102.0	200.9 ± 112.5	100.8 ± 58.8	181.7 ± 73.8	174.4 ± 90.3	105.3 ± 34.5	120.3 ± 37.5	167.4 ± 99.9
ECC phase (% MVC·s^{-1})	64.0 ± 19.4	117.6 ± 47.9	130.0 ± 58.5	61.0 ± 28.0	110.1 ± 54.0	112.9 ± 61.9	67.8 ± 29.5	76.3 ± 29.0	75.8 ± 31.0
CON phase (% MVC·s^{-1})	250.3 ± 61.6	270.2 ± 131.5	276.5 ± 136.4	193.4 ± 151.5	258.0 ± 130.7	253.8 ± 152.0	185.4 ± 55.9	195.1 ± 55.5	191.5 ± 46.7
At start of CON (% MVC)	177.3 ± 68.3	268.2 ± 109.7	283.3 ± 132.4	179.1 ± 113.5	264.2 ± 127.9	254.2 ± 120.4	130.6 ± 47.2	199.6 ± 81.3	206.3 ± 120.3

EMG was normalized to the time of each of the jump phases to account for significant changes in the time of these phases and expressed relative to a MVC assessed using an isometric squat. The AvgIEMG at the start of the CON phase is also displayed.
No significant differences between baseline and posttest were observed for the C group in any of these variables.

velocity during the ECC phase of the SSC jump in this group after training (P = 0.07, ES = 1.11). Hence, in addition to the enhanced contractile capacity developed after training, the mechanisms contributing to enhanced SSC performance discussed above may have also influenced the improved jump squat performance of the WS group after training.

Neither ballistic power nor heavy strength training interventions elicited significant changes in the level of neural activation of the VM, VL, or BF during the 0% 1RM jump squat (Table 7). However, some trends toward practically relevant increases in AvgIEMG were evident after training, especially in the SP (i.e., full jump ES = 0.96, ECC phase ES = 1.18, CON phase ES = 0.47, at start of CON phase ES = 0.90). The current observations are in contrast to previous research that observed a significant percent change in average EMG of the VL during the CON phase of jump squats with 30%, 50%, and 80% 1RM after 8 wk of loaded jump squat training (at 30% or 80% 1RM) (29). However, this previous study reported significant improvements in maximal strength, and considering that the EMG values during the jump squat were not normalized to a MVC, these previous observations may have reflected an increase in maximal voluntary neural activation related to enhanced strength level rather than a specific increase in activation levels during the CON phase of the jump (i.e., unknown whether a similar change in EMG would have been observed during the CON phase of the jump if the EMG values during the jump were normalized to activation during a MVC) (29). Changes to neural activation patterns have been previously reported to contribute to CON performance enhancement during drop jumps after plyometric training (7,34). Previous research indicates that ballistic power training resulted in enhanced rate of EMG rise during a 0% 1RM jump squat and that maximal AvgIEMG was increased after heavy strength training (10). However, any such changes did not translate into increased AvgIEMG during the full jump, ECC, or CON phases or even in the level of activation at the start of the CON phase in the current investigation (Table 7). Therefore, the current study cannot offer any further insight into the role of neural factors in enhancing SSC function after training.

Although the force–velocity loops display very clearly the specific changes to the ECC and CON phases after training, the analysis procedures required to generate such data are time-consuming. The current study indicates that training-induced changes in average ECC power after training were significantly correlated with the main variables commonly used to assess CON performance (peak power $r = -0.65$, average power $r = -0.77$, peak velocity $r = -0.77$, net impulse $r = -0.78$, and peak displacement $r = -0.58$; Table 5). Therefore, in a practical, applied setting where information regarding adaptations to training is required immediately, average ECC power can be used as a simple indicator of whether the training intervention elicited alterations to SSC function.

Influence of strength level on SSC function. Similar to previous research, comparisons between stronger and weaker subjects before the initiation of training revealed that an enhanced strength level was associated with superior CON performance during jumping movements (12,35). In contrast, strength level did not influence ECC power or the power ratio (i.e., ratio between average ECC and CON power) across all loads examined as well as a range of other ECC phase variables during the 0% 1RM jump squat and static jump (Fig. 1 and Tables 2–4). However, the magnitude of the difference between the stronger subjects (SP) and weaker subjects (WP, WS, and C) at baseline in a range of ECC variables (peak and average power and force) was practically relevant (ES = 0.85–1.40). Thus, the intersubject variability may have limited the observation of statistically significant differences between stronger and weaker groups in several ECC phase variables before training. This theory is supported by the fact that an increase in strength (as seen in the WS group) did elicit significant changes in ECC power as well as a range of other ECC phase variables (i.e., ECC force, ECC RFD, and a borderline significant increase in peak ECC velocity (P = 0.08)). The current data indicate that increased strength may be associated with enhanced active stiffness regulation during SSC movements, which is theorized to lead to less fascicle lengthening and greater tendinous lengthening during the ECC phase. As a result, the stronger individual's muscle fibers would be operating closer to their optimal length and at relatively slower velocities, resulting in greater force generation compared with weaker individuals (19,26,27). Therefore, superior strength may be associated with enhanced SSC function (i.e., development of a strategy that more effectively utilizes the ECC phase) that, in conjunction with the increased contractile capacity of stronger individuals, results in superior CON performance.

The magnitude of changes in ECC phase variables after ballistic power training was not influenced by initial strength level (i.e., no significant differences in the training-induced changes existed between SP and WP). However, examination of the force–velocity loops did highlight an interesting dissimilarity between the SP and WP (Fig. 3). Before training, both groups achieved the highest instantaneous force during the CON phase. After 10 wk of training, the highest instantaneous force now occurred during the ECC phase for both groups. The stronger subjects were able to maintain this increased force in the ECC phase for longer throughout the CON phase than the weaker subjects did. This was highlighted by the significant difference between the C and power training groups—both SP and WP had significantly greater force and velocity for 42.0%–77.2% of normalized time to take off, but SP continued to differ significantly from C until 90.8% of normalized time to take off (Fig. 3C). These observations suggest a tendency for stronger subjects to be able to better transfer changes to SSC function in the ECC phase to improved CON performance. It is theorized that having a superior initial strength level may be associated with an enhanced ability to improve force production especially

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at high velocities after ballistic power training (i.e., enhanced ability to translate the momentum developed during the ECC phase into force) owing to increased active stiffness regulation and the subsequent impact on fascicle displacement during SSC movements (26,27). A limitation of the current study was that only male subjects were used, and as such, it is unclear if similar results would be observed in females.

In conclusion, both ballistic power training and heavy strength training elicited significant changes in a multitude of ECC phase variables that were significantly associated with improvements in CON jump performance. These changes were theorized to be driven by the development of a strategy to better utilize the ECC phase during jumping. Specifically, greater unloading allowed for increased negative acceleration and therefore velocity during the countermovement. Increased musculotendinous stiffness resulted in an enhanced ability to translate the momentum developed during the countermovement into force, ultimately leading to improved CON performance (i.e., force, velocity, power, and jump height). Furthermore, these changes were theorized to positively influence the mechanisms involved with SSC (i.e., development of force before CON phase, the interactions between contractile and elastic elements, potentiation of contractile elements, storage and utilization of elastic energy, as well as activation of stretch reflexes), which, in turn, contributed to the improved CON performance. Thus, training-induced alterations in SSC function during the ECC phase contributed to improvements in performance of SSC movements after both ballistic power training and heavy strength training. Previous research have commonly attributed improvements in jump performance after training to alterations in the maximal neural activation, changes to neural activation patterns, or enhanced contractile capacity of the lower limb musculature (7,25,29,34,40). The results of current study indicate that another mechanism driving performance improvements after training is the optimization of SSC function (i.e., development of a strategy to better utilize the ECC phase during jumping, which resulted in improved CON performance).

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