Effects of Unilateral Concentric-Only Dynamic Constant External Resistance Training on Quadriceps Femoris Cross-Sectional Area


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Reference Data

ABSTRACT
The purposes of this investigation were to determine the effects of 8 weeks of unilateral concentric-only dynamic constant external-resistance (DCER) training on the cross-sectional area (CSA) and strength of the trained and contralateral quadriceps femoris muscles. Seventeen men (ages 24.5 ± 4.6 yrs) volunteered for the study and were divided into a training (Tr) group and a control (Con) group. The Tr group trained the nondominant limb with concentric-only leg extension DCER exercise 3 times a week for 8 weeks. Pretraining and posttraining CSA and strength measurements for both the trained and contralateral limbs were determined for all subjects through magnetic resonance imaging scans and concentric DCER strength tests, respectively. The results indicated a significant (p < 0.05) 3.3% mean increase in the CSA of the trained quadriceps femoris muscles, and significant increases in the concentric DCER strength of both the trained (39.7%) and contralateral (14.6%) limbs. These data suggest neural adaptations.

Key Words: strength training, muscle size, hypertrophy

Introduction
The "overload principle" of deLorme and Watkins (16) suggests that a muscle will increase in size and strength when required to perform work beyond that to which it is accustomed. Although the degree to which muscle adaptation occurs is thought to be dependent on a number of factors including the type and intensity of training stimulus, it is generally accepted that there is a close relationship between muscle size and strength. However, hypertrophy is not necessarily a consequence of resistance training (62), and in many cases hypertrophy appears insufficient to fully account for changes in strength (28, 31, 46, 63). Furthermore, it has been suggested (16, 46, 55) that in the early phase of resistance training, strength increases at a rate far greater than can be accounted for by intramuscular morphological adaptations.

Because high mechanical stress is the primary factor that promotes muscle adaptation, it has been suggested (1, 14, 22, 29, 36) that eccentric contractions, which allow for the development of greater maximal tension than can occur through concentric contractions, are essential for optimal muscle development. Several investigations (11, 19, 22, 29, 30, 36, 43) have compared the effects of concentric vs. eccentric resistance training with regard to the inherent ability of each to induce changes in muscle size and/or strength. But the lack of uniformity in experimental designs, coupled with the difficulties in equating workloads, make comparisons between concentric and eccentric training difficult.

Several investigations (3, 4, 11-15, 19, 21, 26, 38-40, 47-50) have examined the potential for isokinetic training, involving only concentric contractions, to induce muscular hypertrophy and/or strength. However, few (5, 22, 29, 30, 43) have studied either of these effects as a result of concentric dynamic constant-external-resistance (DCER) training, and none employed advanced techniques such as magnetic resonance (MR) imaging or computed tomography (CT) scanning. Using MR imaging, which allows for unparalleled visualization of soft tissues such as muscle, it is possible to critically examine several locations in a muscle group and accurately quantify small changes in muscle cross-sectional area (CSA). This scrutinizing of changes in muscle CSA allows us not only to determine the capacity for concentric-only training to induce muscular hypertrophy, but also to compare training-induced changes among individual muscles as well as among locations in a particular muscle.

The cross-training effect is an exercise-induced adaptation that occurs in an untrained, contralateral limb as a result of unilateral training. Although this effect has been studied extensively since its introduction by Scripture (56) in 1894, few studies (26, 27, 38, 47, 52, 59) have examined the effects of concentric-only training on the strength of the contralateral limb, and even fewer studies (26, 38, 47) have examined the potential for this
type of training to induce muscular hypertrophy in a contralateral limb. Furthermore, there are limited data (27) describing the effects of concentric DCER training on a contralateral limb.

Therefore, the purposes of this investigation were to utilize MR imaging to determine the effects of 8 weeks of unilateral concentric-only DCER training on (a) the CSA and strength of the quadriceps femoris muscles of the trained limb, (b) the potential for preferential hypertrophy of a particular muscle in the muscle group or at a certain location within a muscle, and (c) the CSA and strength of the quadriceps femoris muscles of the contralateral limb.

Methods

Seventeen young men volunteered to serve as subjects for this study. They were divided into a training (Tr) group (n = 9; age 23.8 ± 4.8 yrs; body mass 78.2 ± 9.6 kg; Ht 1.79 ± 0.05 m) and control (Con) group (n = 8; age 25.4 ± 4.4 yrs; body mass 76.5 ± 12.1 kg; Ht 1.75 ± 0.07 m). There were no significant (p > 0.05) pretraining differences between groups for age, body mass, height, or any of the CSA or DCER strength measures. All procedures were approved by the Institutional Review Board for Human Subjects, and written informed consent was obtained prior to any testing. All subjects were physically active but none had been involved in resistance training for at least 6 months.

Testing Protocol

Muscle CSA Determination. The Tr group underwent pretraining and posttraining MR imaging (General Electric Signa 1.5-T system) to determine the CSA of each muscle of the quadriceps femoris (vastus lateralis, vastus intermedius, vastus medialis, and rectus femoris) of both thighs at 3 locations (levels). Coronal scans of the thighs were used to determine length of femur from superior border of the head to inferior border of the medial condyle. Three axial scans were then taken at approximately 33, 50, and 67% (proximal, middle, and distal levels, respectively) of this distance (Figure 1).

Repetition time and echo time were set at 600 and 20 ms, respectively. All MR images were transferred to a Macintosh computer for CSA measurement of the individual quadriceps muscles of both limbs using NIH Image software. The same co-investigator, who was unaware of group membership (Tr or Con) or time of testing, took all CSA measurements. During a pilot study,

Figure 1. (Top) Coronal MRI scan indicating the locations (levels) of the thighs where the axial scans were performed. Followed by axial MRI scans at each of the three levels.
the co-investigator showed a test-retest intraclass reliability coefficient of $R \geq 0.99$ for repeated CSA measurements on 10 subjects. The Con group underwent identical MR testing at the same time periods but performed no training.

**Strength Determination.** One repetition maximum (RM) concentric DCER strength was determined on a plate-loaded leg extension resistance training machine (Pro-Star, Blue Springs, MO). Each subject sat with his torso strapped to the backrest and was instructed to hold tightly to the sides of the device. The backrest was adjusted to align the anatomical axes of the knees with the mechanical axis of the machine. Shin pads, attached to the machine's lever arm, were placed against the subject's legs. The shin pads were a fixed distance from the axis of rotation of the lever arm and thus not adjustable. Positioning, however, was consistent for each subject across all tests.

Determination of 1-RM concentric DCER strength involved the application of progressively heavier loads until the subject could not complete a repetition through the full range of motion (approx. 1.57 rad). Subsequent trials were performed with lighter loads until the 1-RM was determined within 2.27 kg. Subjects had 2 min rest between trials. To perform each concentric contraction, the subject lifted the weight unilaterally until the lever arm was approximately in the horizontal plane with the knee slightly flexed. An investigator then took control of the lever arm and lowered the weight. The order of testing of the limbs was randomized for the pretraining testing session and was maintained for the posttraining testing session.

The Con group underwent identical strength testing at the same time periods but performed no training. Reliability estimates calculated from the pretraining and posttraining Con group 1-RM DCER data resulted in an intraclass correlation of 0.98 with a standard error of measurement of 3.3 kg (3.7% of the sample mean).

**Training Protocol**
The Tr group performed 8 weeks of unilateral concentric-only leg extension DCER training on the same device as used for testing. All training involved the non-dominant limb (as determined by kicking preference) 3 times a week. Each training session consisted of 2 or 3 warm-up sets with progressively heavier loads followed by 3 to 5 sets of 6 reps at 80% of concentric 1-RM. For the 1st week of training, the subjects did 3 sets, then 4 sets the 2nd week, then 5 sets for Weeks 3–8. The trained limb was retested for concentric 1-RM every 2 weeks to adjust the training load. To perform concentric-only repetitions (no eccentric action), the subjects lifted (leg extension) the load through the full range of motion and then an investigator lowered the lever arm back to its original position without the subject's help.

**Statistics**
The muscle CSA data were analyzed using a 5-way (group [Tr, Con] × time [pretraining, posttraining] × limb [trained, contralateral] × muscle [vastus lateralis, vastus intermedius, vastus medialis, rectus femoris] × level [proximal, middle, distal]) mixed factorial ANOVA. The 1-RM concentric DCER strength data were analyzed using a 3-way (group × time × limb) mixed factorial ANOVA. An alpha level of 0.05 was considered significant for all tests.

**Results**
The results of the muscle CSA analyses indicated there was no significant 5-way or 4-way interaction, but there was a significant 3-way (group × time × limb) interaction. The variable “muscle” was not involved in the interaction, which indicated that all muscles of the quadriceps femoris exhibited a similar pattern of change as a result of the training (34). Thus, as recommended by Keppel (34), all subsequent analyses were performed with the average muscle CSA values. The significant 3-way interaction was followed up with two (one for each group) 2-way (time × limb) repeated measures ANOVAs. The results of the 2-way ANOVA for the Tr group indicated there was a significant time × limb interaction, which was then followed up with two (one for each limb) 1-way repeated measures ANOVAs. The ANOVA for the trained limb indicated a significant increase in muscle CSA from training. The contralateral limb, however, showed no significant increase in muscle CSA from training. The 2-way ANOVA for the Con group resulted in no significant interactions or main effects, indicating there was no change in muscle CSA for Con as a result of 8 weeks of relative inactivity (Table 1).

The results of the strength data analyses indicated a significant 3-way (group × time × limb) interaction which was followed up with two (one for each group) 2-way (time × limb) repeated measures ANOVAs. The results of the 2-way ANOVA for the Tr group indicated a significant time × limb interaction which was followed up with two (one for each limb) 1-way repeated measures ANOVAs. The 1-way ANOVAs indicated significant changes in 1-RM concentric DCER strength across time for both the trained and contralateral limbs. The 2-way ANOVA for the Con group resulted in no significant interactions or main effects, indicating no change in strength in the Con during the 8-week study (Table 2). Some of the strength data have been reported previously (27).

**Discussion**
It has been suggested that eccentric contractions may be important for muscular hypertrophy (14, 42), and several studies have reported no change in muscle size following concentric-only DCER (5) or concentric-only isokinetic training (11, 13, 19, 40, 48). However, the
results of the present study showing a 3.3% increase (range = 2.2% vastus medialis to 5.4% rectus femoris) in muscle CSA as a result of concentric-only DCER training, as well as other studies involving concentric-only DCER (22, 48), variable resistance (3, 4, 31, 49, 50, 52) or isokinetic (15, 21, 26, 36, 38, 47, 51) training, suggest that an eccentric phase is not required to induce hypertrophy.

The results of this study also support the well-documented potential for concentric-only DCER training to elicit strength gains (5, 18, 22, 29, 30, 43, 57, 58). The 39.7% increase in 1-RM concentric DCER leg extension strength is consistent with other work (5, 29, 58) that reported increases ranging from 14 to 51%. Furthermore, the present study found a 14.6% increase in the 1-RM concentric DCER leg extension strength of the contralateral limb, indicating a cross-training effect.

A number of other studies have reported strength increases in a contralateral limb following combined concentric + eccentric DCER training (10, 24, 41, 46), concentric-only variable resistance training (52), and concentric-only isokinetic training (26, 33, 38). Hellebrandt (25) proposed two possible mechanisms to explain the cross-training effect: (a) diffusion of motor impulses to the contralateral side of the body, and (b) contraction of the musculature on the contralateral side of the body to maintain balance and assume the proper position for the unilateral exercise.

The disproportionate increase in 1-RM strength relative to muscle size found in the present study is consistent with other work (28, 31, 46, 63) that examined strength gains and intramuscular morphological changes during the early phase of training, and is indicative of the complex relationship between both measures of training effectiveness. Although it has been determined that muscle CSA is the major determinant of quadriceps femoris strength, and that there is a linear relationship between muscle size and strength (9, 63), it cannot be assumed that an increase in strength, especially in the early phase of training, is always accompanied by a proportionate hypertrophic effect.

Strength gains in response to resistance training have been attributed to both central and peripheral factors (32, 54, 55). Central factors include volition, motorneuron activity, and coordinated activation of muscles required for both movement and stabilization. They are commonly referred to as the neural component of strength. Peripheral factors involve the intrinsic strength of the muscle, including such elements as size and arrangement of the fibers, architecture of the fibers, packing of the contractile material, and connective tissue attachments.

Studies demonstrating increases in maximal integrated electromyographic amplitude during the first few weeks of training, as well as those demonstrating
rapid increases in strength not accompanied by hypertrophy, indicate that the neural component plays an important role in the early stages of resistance training (23, 46). Furthermore, it is unlikely that morphological changes in the muscle could account for the increases in strength that have been shown to occur as rapidly as within the first training session (61). As the training period progresses, however, increases in strength are associated with muscle hypertrophy (23, 46). These results, along with the disproportionately smaller increases in muscle CSA, suggest the involvement of a neural mechanism.

Several neural mechanisms have been postulated to explain strength increases that are greater than can be accounted for by hypertrophy alone. In general, these have centered around the concept that untrained subjects are unable to fully express strength, thereby resulting in pretraining strength scores that underestimate their true force production capabilities. Through resistance training, however, a neural adaptation occurs, allowing for a greater expression of intrinsic muscular strength. It has been suggested that neural adaptations may involve increased excitatory input, reduced inhibitory input, a combination of both, or an improvement in neuromuscular coordination.

Various techniques including integrated electromyography (iEMG) (23, 36, 37, 46, 60), interpolated twitch (2, 8, 44, 54), and evoked tetany (6, 7, 17, 20, 44) have been employed to identify which neural mechanism is involved. A few studies (23, 37, 46) have demonstrated an increase in iEMG during the first several weeks of training, supporting the contention of increased neural activation. However, others (36, 60) found no such increases in iEMG with training. In addition, several studies employed the interpolated twitch technique—the application of a single supramaximal electrical shock delivered to the motor neuron of a contracting muscle during a maximal voluntary contraction (MVC)—to determine one's ability to fully activate a muscle voluntarily (2, 8, 44, 54). The majority indicate that even untrained subjects, if well-motivated, can achieve full motor unit activation. A third technique is to compare the force produced during an MVC with that produced by tetanic electrical stimulation (6, 7, 17, 20, 44).

The results of these investigations have demonstrated that maximal forces produced voluntarily were equal to those produced via artificial means, also indicating that untrained subjects could achieve full motor unit activation. It should be noted, however, that interpretation of both the interpolated twitch and tetanic electrical stimulation data may be problematic. For example, Harris et al. (24) have shown that twitch interpolation underestimates the MVC and is therefore not a valid index of the degree of voluntary activation. In addition, Kitai and Sale (35) have shown a dissociation between changes in voluntary torque and electrically evoked torque following isometric strength training.

Thus there is conflicting evidence as to whether an untrained subject has a functional muscular reserve that is only available for voluntary utilization after increases in excitatory and/or decreases in inhibitory input have occurred via training.

Another possible neural explanation for strength increases that are greater than can be accounted for by hypertrophy alone involves a training-induced improvement in the ability to coordinate motor unit activation in a muscle, as well as to coordinate prime movers and stabilizers. Komi et al. (37) suggested that training may result in a more efficient summation of motor unit activation, resulting in greater force production. Milner-Brown et al. (45) found that posttraining isometric contractions have EMG patterns that are more synchronous than pretraining ones. Furthermore, Rutherford and Jones (54) suggested that coordination is a learning process that involves the establishment of new central nervous system pathways, and that muscle groups such as the quadriceps may require a certain degree of coordination before they can express increases in intrinsic strength. It was also suggested that a large proportion of the strength increases observed was due to an increased ability to coordinate synergists and stabilizing muscles.

Although it is beyond the scope of this study to identify the mechanisms underlying the changes observed, the disproportionate increase in strength relative to hypertrophy in the trained limb, as well as the strength increase not accompanied by hypertrophy in the contralateral limb, suggest an underlying neural adaptation. It has been suggested (53) that neural adaptations provide a "conservative" mechanism for enhancing performance early in resistance training without the "costly metabolic event" of the accumulation and maintenance of contractile proteins. In this way, neural mechanisms provide a rapid, accommodating approach to meeting potentially transient increases in the demands on the muscle. More research is needed to identify the specific neural mechanisms responsible for strength gains early in resistance training programs.

**Practical Applications**

The present findings suggest that an 8-week weight-training program involving only concentric contractions was sufficient to elicit increases in both size and strength of the quadriceps femoris muscle group. Therefore, eccentric contractions were not required for improving muscle size and strength. Furthermore, the untrained limb exhibited significant improvements in strength even though it was not directly involved in the training. This has important implications for individuals who have an immobilized limb due to injury or surgery. By training the nonimmobilized limb, it may be possible for the muscles in the immobilized limb to retain, or even improve, their strength.
References


