Effects of Unilateral Eccentric-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 unilateral eccentric-only dynamic constant external resistance (DCER) training on the cross-sectional area (CSA) and strength of the trained and contralateral quadriceps femoris muscles. Sixteen young men (age 24.4 ± 3.7 yrs) volunteered to serve as subjects and were divided into a training (Tr) group and a control (Con) group. The Tr group trained the nondominant limb with eccentric-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 using magnetic resonance imaging scans and eccentric DCER strength tests, respectively. The results indicated there was no significant change in CSA of any muscles of the quadriceps femoris of either the trained or contralateral limb. There was, however, a significant increase in the eccentric DCER strength of both the trained (29%) and contralateral (17%) limbs. The strength changes that were unaccompanied by hypertrophy suggest a neural adaptation.

Key Words: strength training, muscle size, hypertrophy

Introduction

It is generally accepted that concentric and eccentric training provide different stimuli to a working muscle and therefore can elicit different adaptations. Because a greater load can be placed on a muscle performing eccentric vs. concentric contractions, it was originally thought that greater strength gains could be attained through eccentric training (21). Few investigations have reported greater strength gains with eccentric training (43, 49), however, and because of the difficulties involved in equating workloads, direct comparisons between both types of training are difficult.

The strength of a muscle is determined in part by its size. Various techniques including muscle biopsy (11, 12, 24, 45, 50), anthropometry (3, 18, 23), ultrasound (36, 45, 71), computed tomography (CT) (39, 48, 56, 59, 65), and magnetic resonance (MR) imaging (31, 32, 55, 58) have been used to examine the muscular hypertrophy associated with resistance training. While many studies have reported changes in muscle size following concentric + eccentric (17, 23, 25, 48, 56, 58, 61, 65, 67) and concentric-only (17, 31, 32, 39, 45, 50, 55, 59) resistance training, little is known about a muscle’s hypertrophic response to eccentric-only training (29, 50, 63). Furthermore, of the few studies that have examined eccentric-only training, none have used MR imaging, which has unparalleled capabilities for examining soft tissues such as muscle and allows for comparisons of training-induced changes in cross-sectional area (CSA) among individual muscles as well as among locations in a particular muscle.

The cross-training effect is a phenomenon that involves the transfer of ability (27) or strength (8, 10, 28, 33, 34, 45, 54) achieved during unilateral training to an untrained, or contralateral, limb. Although not all studies (31, 63, 71, 72) have reported an increase in strength in a contralateral limb following unilateral training, this phenomenon has been shown to occur following concentric + eccentric (10, 26, 47, 54) and concentric-only (40, 45, 60) resistance training.

There is limited research (6, 30, 33, 70), however, as to the effects of eccentric-only resistance training on the strength of a contralateral limb. In addition, while several studies have examined the effects of unilateral concentric + eccentric (7, 62, 71), eccentric-only (29), and concentric-only (31, 35, 45, 55, 60) resistance training on the hypertrophic response of the contralateral limb, no significant hypertrophy in a contralateral limb has been reported. Furthermore, no studies to date have examined the potential for eccentric-only dynamic constant-external-resistance (DCER) training to induce hypertrophy in a contralateral limb.

Therefore, the purposes of this investigation were to use MR imaging to examine the effects of unilateral...
eccentric-only DCER training of the leg extensor muscles on: (a) the CSA and strength of the quadriceps femoris muscles of the trained limb; (b) the potential for preferential hypertrophy of a certain muscle in the muscle group or at a particular location within a muscle; and (c) the CSA and strength of the quadriceps femoris muscles of the contralateral limb.

Methods

Sixteen young men volunteered to serve as subjects for this investigation. They were divided into a training (Tr) group \((n = 9; \text{age } 24 \pm 3 \text{ yrs}; \text{body mass } 85 \pm 8 \text{ kg; Ht } 1.81 \pm 0.06 \text{ m})\) and a control (Con) group \((n = 7; \text{age } 25 \pm 5 \text{ yrs}; \text{body mass } 77 \pm 13 \text{ kg; Ht } 1.75 \pm 0.08 \text{ m})\). There were no significant \((p > 0.05)\) pretraining differences between groups for age, body mass, height, or any of the CSA or eccentric 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 MR imaging (General Electric Signa 1.5-T system) immediately prior to the training period (pretraining) and immediately after the training period (posttraining). The MR images were used to determine the CSA of each muscle of the quadriceps femoris (vastus lateralis, vastus intermedius, vastus medialis, rectus femoris) in both thighs at three locations. Coronal scans of the thighs were used to determine femur length from the superior border of the head to the inferior border of the medial condyle. Three axial scans were then taken at approximately 33, 50, and 67% (proximal, middle, and distal levels) 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 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. The Tr group underwent pretraining and posttraining testing for unilateral one-repetition maximum (1-RM) eccentric DCER leg extension strength on a plate-loaded leg extension resistance training machine (Pro-Star, Blue Springs, MO). Each

![Figure 1](image-url)  

**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.
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 eccentric DCER strength involved the application of progressively heavier loads until the subject could not satisfactorily complete a repetition. Subsequent trials were performed with lighter loads until the 1-RM was determined within 2.27 kg. Subjects rested 2 min between trials. During each trial an investigator lifted the load until the lever arm was slightly above the horizontal plane. The subject then indicated that he had control of the load, at which time the investigator gently released control.

Because of the design of the leg extension machine, and to avoid knee joint discomfort, it was decided during pilot data collection to define a satisfactory repetition as the ability to stop the rotation of the lever arm at <0.09 rad below the horizontal plane with the knee slightly flexed (<0.18 rad). The subject was then required to lower the weight slowly (1 to 2 sec) until the lever arm made contact with a horizontal support. These procedures resulted in highly reliable (R = 0.97) determinations of 1-RM eccentric DCER strength. The order of testing of the limbs was randomized during the pretraining session and was maintained for the posttraining session. The Con group underwent identical strength testing at the same time periods but performed no training.

**Training Protocol**

The Tr group performed 8 weeks of unilateral eccentric-only DCER training of the leg extensor muscles of the nondominant limb (as determined by kicking performance) 3 times a week. All training was done on the same device as used for testing. Each training session consisted of 2 to 3 warm-up sets with progressively heavier loads, followed by 3 to 5 sets of 6 reps at 80% of the eccentric 1-RM. For the 1st week of training the subject performed 3 sets; then 4 sets the 2nd week, then 5 sets for Weeks 3–8. The trained limb was tested for eccentric 1-RM every 2 weeks to adjust the training load. To perform eccentric-only repetitions (no concentric action), an investigator lifted the load, without help from the subject, until the subject’s leg was within 0.18 rad of full extension. The subject then slowly lowered the lever arm back to its original (vertical) position and was instructed to lower the lever arm in approximately 1 to 2 sec. Therefore the velocity for the eccentric-only DCER repetitions was approximately 0.79 to 1.57 rad · s⁻¹.

### Table 1

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<th>Distal level</th>
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VL = vastus lateralis, VI = vastus intermedius, VM = vastus medialis, RF = rectus femoris.

### 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 eccentric 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.
Table 2
1-RM Eccentric DCER Strength in kg (M ± SEM)

<table>
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<tr>
<th></th>
<th>Pretraining</th>
<th>Posttraining</th>
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<td>Nondom. limb</td>
<td>Dominant limb</td>
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<tr>
<td>Training group*</td>
<td>48.1 ± 3.4</td>
<td>51.8 ± 2.9</td>
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<tr>
<td>Control group</td>
<td>43.4 ± 4.1</td>
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*Nondominant limb = trained limb and dominant limb = untrained limb in the training group.

Results

The results of muscle CSA data analysis indicated there were no interactions or main effects involving the variable “time” (Table 1). The primary focus of the present study was to determine changes in muscle CSA as a result of eccentric DCER training. Therefore, significant interactions or main effects not involving “time” were not of interest in this study.

The results of the 1-RM eccentric DCER strength data analysis indicated a significant 2-way (group × time) interaction. The variable “limb” was not involved in the interaction, indicating that both the trained and contralateral limbs exhibited the same pattern of change as a result of training (41). Therefore, as recommended by Keppel (41), the significant group × time interaction was followed up with a paired t-test (pretraining vs. postraining) for each group, using 1-RM eccentric DCER strength values collapsed (averaged) across limbs. The results of the t-tests showed there was a significant increase in strength for the Tr group as a result of training; however, there was no significant change in strength for the Con group (Table 2). Some of the strength data have been reported previously (32, 70).

Discussion

The results of the present study are consistent with those of Duncan et al. (18) and Ben-Sira et al. (3) which reported no evidence of muscular hypertrophy as a result of eccentric-only training. Duncan et al. found no change in thigh girth as a result of 6 weeks of eccentric-only isokinetic training, whereas Ben-Sira reported no change in thigh girth as a result of 8 weeks of eccentric-only DCER training. Jones and Rutherford (39), however, reported an increase in quadriceps CSA as a result of 12 weeks of eccentric-only variable resistance training, and Mayhew et al. (50) reported an increase in Type II muscle fiber CSA as a result of 4 weeks of eccentric-only isokinetic training.

The absence of a significant hypertrophic effect in the present study may be a function of the training volume (loads × repetitions × sets) and/or short duration of the training program. Because of differences in testing techniques for 1-RM determination, it is difficult to make comparisons between the training loads used in different investigations; however, it appears that the training volume in the present study was lower than that of Jones and Rutherford (39), who trained subjects at 145% of their concentric 1-RM, and Mayhew et al. (50), who used 5 sets of 10 reps vs. the 3 to 5 sets of 6 used in the present study. Furthermore, the Jones and Rutherford study was 4 weeks longer than the present study.

In addition, it is important to note that whenever the training load is based on a percentage of maximum, the pretraining 1-RM, and therefore the training load, is largely dependent on the criteria used to define a successful repetition. Furthermore, it is much more difficult to define a successful eccentric 1-RM value than a successful concentric one. In the present study, a successful eccentric repetition was defined as one in which the subject could lower the weight in a “slow and controlled” manner. This required the subject to take the weight from the investigator when the lever arm was slightly above the horizontal plane, hold it at full leg extension < 5° below the horizontal plane, demonstrate control, and then begin lowering the weight slowly, reaching the end of the range of motion in approximately 1 to 2 sec.

Due to the design of the leg extension machine and the anatomy of the quadriceps muscle group, the greatest resistance occurred at the point in the range of motion where the muscle length was the shortest. This resulted in 1-RM values that were limited by the amount of weight that could be held (isometrically) at the weakest point in the range of motion (near full extension). Thus the strict criteria used to determine pretraining eccentric 1-RM values, as well as those determined after each 2 weeks of training, may have resulted in lower training loads than those of previous investigations (39, 50) that employed a percentage of concentric 1-RM to determine the eccentric training load.

We have previously reported (33) the increase in 1-RM eccentric DCER leg extension strength for the training group. In addition, the eccentric DCER training resulted in increases in isometric strength at 45 and 75° (70). This indicates that 1-RM eccentric DCER leg extension strength increased approximately 29% as a result of the training program. This increase is consistent with the 4 to 61% range of increases in concentric, eccentric, and isometric strength reported in other studies using eccentric-only resistance training (3, 18, 37-39, 43, 49, 50, 66).

The reasons for the wide range of strength changes in those studies are unclear, but most likely reflect differences in both training and testing protocols as well as differences in the types of strength measured. In the present study, the increase in strength that was not accompanied by hypertrophy indicates the involvement of a neural adaptation (12, 16, 43, 54, 68, 69). Neural adaptations are thought to account for strength changes.
during the first few weeks of a resistance training program (54, 64). Several types of neural mechanisms have been suggested, including an increase in the excitatory-to-inhibitory motor unit ratio, synchronization of motor unit impulses, an increase in the coactivation of agonist muscles, and a decrease in the coactivation of antagonist muscles.

Integrated electromyography (iEMG) studies tend to indicate that an increase in neural activation occurs early in resistance training (24, 44, 54), and DeLuca et al. (13) suggest it is the high threshold motor units, those responsible for the “largest and fastest twitch contractions,” which many untrained people may not be able to recruit or raise to the optimum firing rate. However, other studies using interpolated twitch (2, 9, 51, 63) and evoked tetany (4, 5, 15, 19, 51) techniques tend to indicate that even untrained subjects, if well-motivated, can achieve full motor unit activation.

It should be noted, however, that interpretation of both interpolated twitch and tetanic electrical stimulation data may be problematic. For example, Harris et al. (26) have shown that twitch interpolation underestimates MVC and is therefore not a valid index of the degree of voluntary activation. In addition, Kitai and Sale (42) found a dissociation between changes in voluntary torque and electrical evoked torque following isometric strength training. Thus there is conflicting evidence as to whether an untrained subject has a functional reserve that is only available for voluntary utilization after increases in excitatory and/or decreases in inhibitory input have occurred via training.

Alterations in the synchronization of motor unit impulses is another factor that may account for strength increases in the absence of hypertrophy. Although Milner-Brown et al. (52) have reported posttraining isometric EMG patterns that are more synchronous than pretraining EMG patterns, it seems unlikely that this alone could account for increases in muscle force production, since synchronous stimulation of muscle produces less force than asynchronous stimulation (46). Therefore, the advantages associated with increased motor unit synchronization that have been reported to occur as a result of resistance training remain unclear.

Coordinated coactivation of agonists and synergists, however, is a neural adaptation that would have a positive effect on force production. Rutherford and Jones (63) suggest 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. Furthermore, Behm (1) hypothesizes that the coordinated activation of synergist muscles may be less than optimal in untrained individuals. The results of the present study suggest that a neural adaptation, such as an increase in coordinated coactivation of agonists and synergists, may be at least partly responsible for the strength increase not accompanied by hypertrophy.

Cross-training is a phenomenon that involves changes in the contralateral (untrained) limb as a result of unilateral training. The cross-training effect has been attributed to neural adaptations involving (a) the diffusion of motor impulses to the contralateral side of the body and (b) contraction of the musculature on the contralateral side to maintain balance and assume the proper position for the unilateral exercise (27). Although contraction of the musculature on the contralateral side of the body may explain changes in a contralateral limb, measurements of EMG activity in a contralateral limb during unilateral training indicate that the magnitude of the EMG is rather low and insufficient to represent a training stimulus (14, 22, 53, 57).

In addition, while it is generally accepted that significant hypertrophy of a contralateral limb is not a result of unilateral training (7, 31, 35, 45, 55, 60, 62, 71), there is no consensus on contralateral limb strength increases. Several studies (6, 10, 26, 33, 34, 40, 45, 47, 54, 60, 70) have reported significant increases in contralateral limb strength, while others (31, 63, 71, 72) have not. Furthermore, there is limited research (6, 33, 70) examining the cross-training effect as a result of unilateral eccentric-only training. We have previously reported the increases in 1-RM DCER leg extension strength (33) in the present study, as well as increases in isometric strength at 45 and 75° (70) in the contralateral limb following unilateral eccentric-only DCER training. Bonde-Petersen (6), however, found no increase in contralateral limb isometric strength following 36 days of 10 unilateral eccentric forearm flexion exercises per day. It was also reported (6), however, that this training stimulus did not result in an isometric strength increase in the trained limb.

The 17% increase in contralateral limb eccentric DCER 1-RM in the present study is consistent with the 8 to 25% increases in strength reported in a contralateral limb following unilateral training consisting of combined concentric + eccentric DCER (10, 26, 47, 54), concentric-only variable resistance (60), and concentric-only isokinetic (40, 45) exercises. The significant strength increase, in the absence of contralateral limb muscle hypertrophy, further supports the contention that a neural adaptation has occurred. Enoka (20) stated, “it is probable that the cross-training phenomenon reflects a centrally located neural adaptation.” Such a neural adaptation could account for strength increases in both a trained and a contralateral limb without the acquisition of additional contractile proteins.

In summary, the 8 weeks of unilateral eccentric-only DCER training in the present study did not provide a sufficient stimulus for muscular hypertrophy. However, the training did result in increases in the 1-RM eccentric-
Eccentric DCER leg extension strength of both the trained (29%) and contralateral (17%) limbs. The strength changes, therefore, were attributed to neural adaptations.

Practical Applications

The present findings suggest that the 8-week weight training program, consisting of 3 to 5 sets of 6 eccentric contractions at 80% of the eccentric 1-RM, was insufficient to elicit muscular hypertrophy. The training program was sufficient, however, to elicit significant improvements in the strength of the quadriceps femoris muscle groups of both the trained and contralateral limbs. This has important implications for individuals with a limb that is immobilized due to injury or surgery. Training the nonimmobilized limb may provide sufficient neural stimuli to the immobilized limb to result in retention, or even improvement, in the strength of the immobilized limb.

References