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The Effects of Accentuated Eccentric Loading on Strength, Muscle Hypertrophy, and Neural Adaptations in Trained Individuals

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ABSTRACT

The purpose of this study was to compare the strength and neuromuscular adaptations for dynamic constant external resistance (DCER) training and dynamic accentuated external resistance (DAER) training (resistance training employing an accentuated load during eccentric actions). Male subjects active in resistance training were assigned to either a DCER training group ($n = 10$) or a DAER training group ($n = 8$) for 9 weeks. Subjects in the DCER group performed 4 sets of 10 repetitions with a load of 75% concentric 1 repetition maximum (RM). Subjects in the DAER group performed 3 sets of 10 repetitions with a concentric load of 75% of 1RM and an eccentric load of approximately 120% of concentric 1RM. Three measures reflecting adaptation of elbow flexors and extensors were recorded pretraining and posttraining: concentric 1RM, muscle cross-sectional area (CSA), and specific tension. Strength was assessed at midtraining periods. No significant changes in muscle CSA were observed in either group. Both training groups experienced significant increases in concentric 1RM and specific tension of both the elbow flexors and extensors, but compared with DCER training, DAER training produced significantly greater increases in concentric 1RM of the elbow extensors. These results suggest that, for some exercises, DAER training may be more effective than DCER training in developing strength within a 9-week training phase. However, for trained subjects, neither protocol is effective in eliciting muscle hypertrophy.

Key Words: concentric 1RM, muscle cross-sectional area, resistance training

Reference Data: Brandenburg, J.P., and D. Docherty. The effects of accentuated eccentric loading on strength, muscle hypertrophy, and neural adaptations in trained individuals. *J. Strength Cond. Res. 16(1):25–32. 2002.*

Introduction

Improvement in muscle strength resulting from progressive resistance exercise programs is attributed to increased skeletal muscle mass (29) and neural adaptation (25). It has been suggested that heavy resistance training, emphasizing high-load and low-repetition (4–6 repetition maximum [RM]) exercises will produce neural adaptations, whereas moderate loads and repetitions (8RM–10RM) are more associated with muscular hypertrophy (14).

Exercises performed using free weights and weight-training machines use the same load for concentric and eccentric muscle actions and are referred to as dynamic constant external resistance (DCER) training (31). Although higher levels of force generation are possible during eccentric actions (5), the training load is normally set by the maximum concentric force. Consequently, the relative intensity of the load is reduced during the eccentric component of each repetition of DCER training. If neuromuscular adaptations are dependent on the magnitude of the training load (1, 4) as well as the number of repetitions (14), it is possible that the muscle is not receiving the optimal stimulus during DCER training. A protocol that increases the load during the eccentric action while still permitting 8–10 repetitions, may produce greater neuromuscular adaptation than typical DCER training permits (3). High loads during the eccentric muscle actions are associated with greater muscle damage (27) and possibly, subsequent hypertrophy (15). Motor unit recruitment during controlled eccentric actions has also been associated with preferential recruitment of fast twitch fibers (19), which have demonstrated a greater hypertrophic potential than slow twitch fibers (15). Additionally, high eccentric loads may reduce neural inhibition that would lead to greater concentric force generation (32).

Although there is unequivocal support for the combined concentric and eccentric actions in DCER training compared with the use of only concentric actions (4, 15, 22) and only eccentric actions (3), there is a paucity of research that has investigated the effects of adjusting the eccentric load to provide an additional stimulus. Godard et al. (9) compared the effects of 1 set of 8–12 repetitions for 10 weeks of strength training in a group using the same resistance for unilateral knee extensor concentric and eccentric actions to a group using an accentuated resistance during the eccentric action of all repetitions. They found that both groups increased concentric knee extensor torque, but there was no difference between the groups. It is possible that a low volume of training along with the inexperienced training status of the subjects compromised the training effect and accounted for the lack of difference between the groups. In addition, training volume was not equated between the groups, and the study used an isokinetic form of training not usually employed in resistance training programs.

Therefore, the purpose of this investigation was to compare the effects of 2 strength training programs on maximal strength of trained individuals. One program used DCER training at an intensity of 75% of 1RM for 4 sets of 10 repetitions, and the other program, dynamic accentuated external resistance (DAER), used the same concentric load but adjusted the load to approximately 110–120% of concentric 1RM during the eccentric action for 3 sets of 10 repetitions. The different number of sets performed by each group approximately equated the training volume. In addition, muscle cross-sectional area (CSA) and specific tension were measured to assess the contribution of neural and hypertrophic adaptations to changes in strength. It was hypothesized that training with the increased load during the eccentric action would elicit greater strength gains, muscle hypertrophy, and neural adaptation than training with the same load for the concentric and eccentric actions.

Methods

Subjects

Twenty-three university-aged male subjects who were active in resistance training volunteered as subjects for this study. The subjects were considered trained because they had all been strength training for a minimum of 1 year (8) and demonstrated the ability to perform a bench press with a load equal to body weight (2, 23). The subjects were randomly assigned to either a DCER training group or a DAER training group in which the resistance was adjusted to match concentric and eccentric strength. Complete explanations of testing and training procedures were provided to the subjects before they gave written informed consent. The University of Victoria Human Ethics Committee granted approval for the study.

Five subjects, 1 from the DCER group and 4 from the DAER group, withdrew from the study over the 9-week duration. Consequently, 10 and 8 subjects remained in the DCER and DAER training groups, respectively. The height and weight characteristics of the subjects as well as their preacher curl and supine elbow extension 1RM values are shown in Table 1. Two of the 4 subjects that withdrew from the DAER group experienced forearm pain possibly associated with the augmented eccentric loads. The remainder of the subjects withdrew because they were unable to comply with the training schedule.

Table 1. Mean (±*SD*) height and weight characteristics and concentric 1RM values for the elbow flexors and extenagsors for the subjects of the DCER ($n = 10$) and DAER ($n = 8$) training groups.*

			Concentric 1RM	
Group	Height, cm	Weight, kg	Elbow flexor, kg	Elbow extensor, kg
DCER	178.0 (6.2)	81.6 (5.9)	42.2 (7.0)	47.6 (7.5)
DAER	179.9 (5.8)	80.4 (2.8)	44.2 (5.0)	48.8 (7.6)

* RM = repetition maximum; DCER = dynamic constant external resistance; DAER = dynamic accentuated external resistance.

Procedures

Training. Subjects in both groups trained 2 times per week for the first 2 weeks and then 3 times per week for the remainder of the 9-week training period. The training exercises performed were selected to exercise the elbow flexors (preacher curl) and elbow extensors (supine elbow extension). Body positions and range of motion during training were similar to those adopted for testing conditions. The tempo of training was controlled so that each concentric and eccentric action lasted for 2 seconds. Rest periods of 3 minutes separated training sets for all subjects. A minimum of 48 hours was required between training sessions. The training load for both the concentric and eccentric actions was increased when the average number of repetitions performed per set in a training session became greater than 10. Training was supervised to confirm that correct training procedures and loads were used. The order of performance of these exercises was randomized from session to session. Subjects were asked to refrain from other resistance training incorporating the elbow flexors and extensors.

The DCER group performed 4 sets of 10 repetitions of each exercise to concentric failure at a training intensity of approximately 75% of concentric 1RM. The DAER group performed 3 sets of 10 repetitions of each exercise to concentric failure, using a training intensity that varied from concentric to eccentric action. The intensity for the concentric action was the same as the load for the DCER group (75% of 1RM), whereas eccentric actions were performed at a load of approximately 110–120% of concentric 1RM. Training partners immediately adjusted the weight at the end of each action to ensure that the load was correct for the next action.

Although training intensity differed between the training groups, volume was approximately equated. Training volume was defined as the number of sets × the number of repetitions × the training load (22, 30). As training load was altered during the DAER protocol, training volume was established by separating the number of repetitions performed into the number of concentric and eccentric actions completed. Thus, training volume for the DCER group was calculated as (4 sets) × ([concentric actions × 75% of concentric 1RM] + [eccentric actions × 75% of concentric 1RM]); the value was expressed as units per exercise and equaled 60 units. The training volume for the DAER group was (3 sets) × ([concentric actions × 75% of 1RM] + [eccentric actions × approximately 120% of 1RM]), which equaled 58.5 units.

Testing

Evaluation of strength, muscle CSA, and specific tension occurred before and on completion of the 9 weeks of resistance training. Additionally, strength was assessed after 3 and 6 weeks of training. Subjects were asked to refrain from activity involving the elbow flexors and extensors 48 hours before evaluation of muscle CSA. Strength was assessed on the day after the measurement of muscle CSA for both the pretraining and posttraining tests to avoid the effects of maximal strength testing on magnetic resonance imaging (MRI).

Strength. Concentric 1RMs of the elbow flexors and extensors were measured while subjects performed a seated bilateral preacher curl and a supine elbow extension, respectively.

Maximal concentric strength (concentric 1RM) was the maximum resistance that a muscle could overcome while shortening during a maximal voluntary effort. Concentric 1RM was determined through successive trials of increasing intensity. The magnitude of the load increased or decreased until the load was established when only 1 contraction could be performed. Before testing, subjects completed 2 sets of 10 repetitions at a load approximating 50% of estimated 1RM. A 4-minute rest period separated all warm-up and testing sets.

1RM Preacher Curl. Seated bilateral biceps curls were performed on a preacher curl bench with a curling bar (Aloyd Fitness Equipment, Victoria, British Columbia, Canada). Subjects were seated on the bench with both feet flat on the floor. The height of the preacher bench pad was adjusted so that the trunk of each subject was straight, while the posterior aspect of the arms and axillae rested on the pad. The height of the pad was recorded to standardize all testing sessions. Using a supinated grip, subjects grasped the curling bar at the narrowest width. Subjects initiated the concentric biceps test with both arms resting on the pad and the elbow flexed at 10° (0° equaled full extension). A successful trial was defined when full elbow flexion (the point of tissue contact between the forearm and biceps) was obtained.

1RM Supine Elbow Extension. Assessment of elbow extensor strength was made with subjects positioned on a bench in the supine position. The subjects were instructed to maintain contact with the bench at the position of the head, shoulder blades, buttocks, and thighs, with the feet positioned flat on the floor. Using a pronated grip at the narrowest width, subjects held the curling bar above the forehead with both arms perpendicular to the bench and elbows at shoulder width. Determination of concentric 1RM was made at an elbow joint angle of 100° elbow flexion (0° equaled full extension), and a repetition was considered successful when full elbow extension was achieved. Joint angles were established with a goniometer (Fitsystems Inc., Calgary, Alberta, Canada).

Muscle CSA. Pretraining and posttraining measurement of elbow flexor and elbow extensor CSA of the right arm was performed through nuclear MRI (1.0 T, Signa Horizon, General Electric, Milwaukee, WI). To enhance resolution, the MRI was performed with the right arm inside a knee coil. Relaxation and echo times were set at 525 and 12 milliseconds, respectively. The field of view during imaging was 16 cm^2. Humeral length, established with anthropometric measures, was defined as the distance between the distal end of the olecranon process and the acromion process (16). The midpoint of the humerus was then determined from a coronal scan in which the olecranon process was identifiable. Twelve axial scans, each 5 mm thick, were taken at 10-mm intervals, beginning from 70 mm superior to the midpoint of the humerus. Because of unclear resolution of the extreme proximal and distal images, only 6 slices (2 proximal, 2 midpoint, and 2 distal) were used to represent the CSA of the elbow flexors and extensors. The level of the scans that were measured to determine CSA was the same between individuals and within individuals before and after training. CSA of elbow flexors and extensors was measured as the maximum value of the 6 slices as well as the average value of the 2 proximal, 2 midpoint, and 2 distal images. The CSA of all pretraining and posttraining images was measured after the completion of training. During CSA measurement, the tester was unaware of whether the image was from the pretraining or posttraining period. Test-retest reliability for repeated CSA measures of the same MRI scan produced an R value of 0.996.

Specific Tension. Specific tension (kilograms per square centimeter) for each muscle group was determined by dividing the concentric 1RM value by the maximal CSA measured. Since specific tension was determined from bilateral concentric 1RM measurements and unilateral CSA, the actual values of specific tension may be misleading. However, as the testing pro-

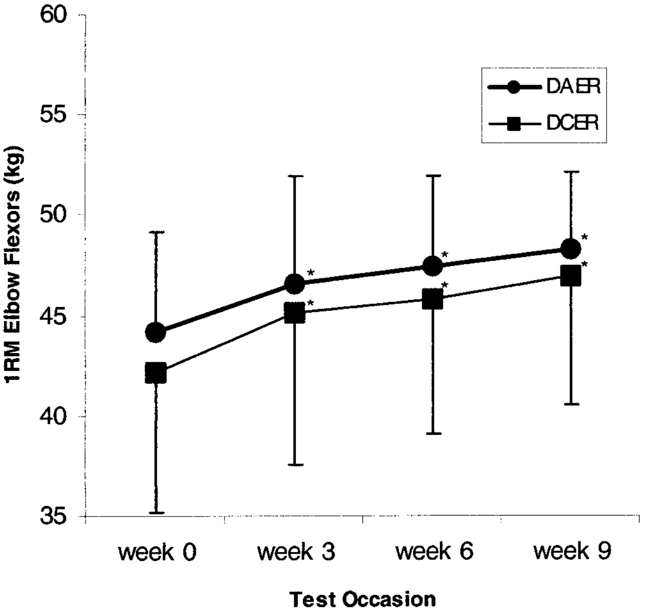

Figure 1. Mean (±*SD*) values for concentric 1RM of the elbow flexors over the duration of the study (* Indicates significant difference from week 0, $p < 0.05$). RM = repetition maximum.

cedures were the same before and after training, any changes in specific tension could still be attributed to neural adaptation.

Statistical Analyses

Differences in muscle CSA and specific tension data were examined using a 2 by 2 analysis of variance (ANOVA) (group by time) with repeated measures on the second factor. A 2 by 4 (group by time) ANOVA with repeated measures on the second factor was performed to analyze strength data. A series of 2 by 2 (group by time) ANOVA tests with repeated measures on the second factor were used to determine at what point differences in strength occurred. The α level was set at $p \leq 0.05$.

Results

Strength

The effects of the 2 resistance training programs on elbow flexor concentric 1RM and elbow extensor concentric 1RM are presented in Figure 1 and Figure 2, respectively. DCER training significantly increased concentric 1RM of the elbow flexors (11%) and extensors (15%). Similarly, DAER training significantly increased concentric 1RM of the elbow flexors (9%) and extensors (24%). Furthermore, elbow extensor strength significantly increased at each testing occasion. The increases in elbow extensor 1RM were significantly greater for the DAER training than for the DCER training.

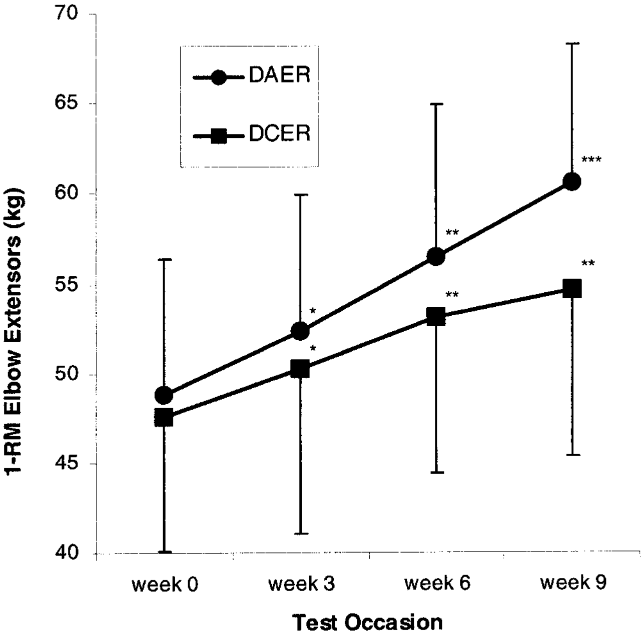

Figure 2. Mean (±*SD*) values for concentric 1RM of the elbow extensors over the duration of the study (* Indicates significant difference from week 0, ** indicates significant difference from week 3, and *** indicates significant difference from week 6 and from the DCER group at week 9, $p < 0.05$). RM = repetition maximum; DCER = dynamic constant external resistance.

Table 2. Mean (±*SD*) pretraining and posttraining maximum elbow flexor and extensor CSA measurements of the DCER ($n = 10$) and DAER ($n = 8$) training groups.*

Muscles	DCER	DAER
Elbow flexors		
Pretraining, cm^2	28.7 (4.06)	30.52 (3.64)
Posttraining, cm^2	29.6 (4.69)	30.43 (2.65)
Elbow extensors		
Pretraining, cm^2	35.43 (7.08)	36.34 (3.81)
Posttraining, cm^2	36.03 (7.26)	36.94 (3.16)

* CSA = cross-sectional area; DCER = dynamic constant external resistance; DAER = dynamic accentuated external resistance.

Muscle CSA

The effects of the 2 resistance training programs on maximal CSA of the elbow flexors and extensors are illustrated in Table 2. No significant differences in any of the muscle CSA variables were produced by either DCER training or DAER training.

Specific Tension

The means and *SD*s for specific tension of the elbow flexors and extensors after resistance training are summarized in Table 3. DCER training significantly increased specific tension of the elbow flexors (9%) and extensors (13%). Similarly, DAER training significantly

Table 3. Mean (±*SD*) pretraining and posttraining elbow flexor and extensor specific tension values of the DCER ($n = 10$) and DAER ($n = 8$) training groups.†

Muscles	DCER	DAER
Elbow flexors		
Pretraining, kg·cm^{-2}	1.47 (0.14)	1.46 (0.18)
Posttraining, kg·cm^{-2}	1.60 (0.12)*	1.59 (0.08)*
Elbow extensors		
Pretraining, kg·cm^{-2}	1.36 (0.20)	1.34 (0.18)
Posttraining, kg·cm^{-2}	1.54 (0.25)*	1.64 (0.16)*

† DCER = dynamic constant external resistance; DAER = dynamic accentuated external resistance.

* Represents significant difference from pretraining value ($p < 0.05$).

increased specific tension of the elbow flexors (9%) and extensors (22%). The effects of the 2 types of training on muscle specific tension were not significantly different.

Discussion

The purpose of this study was to compare DCER training and load-adjusted concentric-eccentric resistance (DAER) training on strength and neuromuscular adaptations. Both types of training induced significant improvements in elbow flexor and elbow extensor concentric strength. Improvements in elbow flexor strength were similar in response to both types of training (Figure 1). DAER training, however, produced significantly greater development in elbow extensor strength compared with DCER training (Figure 2).

Godard et al. (9) compared accentuated and nonaccentuated eccentric training programs and found that both groups demonstrated large significant increases in leg extension strength, but there were no differences between the 2 groups. The present study found significant improvements in both elbow flexor and extensor strength for the DCER (nonaccentuated eccentric action) and DAER (accentuated eccentric action) groups, but there was a significant difference between the 2 groups in elbow extensor strength. In addition, the magnitude of the increase in strength for the subjects in the study of Godard et al. (9) (101–106%) were far in excess of the increases demonstrated in the present study (9–24%). Godard et al. (9) also reported modest but significant hypertrophy (as measured by thigh girth) for both groups, whereas in the present study, no changes in muscle CSA occurred in either group. Although both studies used an accentuated eccentric training protocol with similar loads, the differences in the results may be accounted for by the untrained status of the subjects in the study of Godard et al. (9) and their isokinetic mode of training. The large gains in strength experienced by their subjects may have been attributable to a considerable learning effect from training with isokinetic muscle actions in addition to the neural adaptations normally associated with individuals unaccustomed to resistance training. Furthermore, their untrained status would increase their responsiveness to any training stimulus. Consequently, the nonaccentuated eccentric load may have been an adequate stimulus for the untrained subjects, and the added resistance in the accentuated program may not have provided any additional advantage.

Increases in the elbow flexor strength for the DCER and DAER groups (9% and 10%, respectively) in this study were less than the 13–25% increases in elbow flexor strength reported in other studies in subjects with a resistance training background (16, 18). Although these studies employed DCER training, the greater increases in strength may be attributed to multiple exercises, more sets, and greater loads. Furthermore, differences in pretraining status may account for the reduced improvements found in this study.

Kawakami et al. (13) demonstrated 20–32% increments in the elbow extensor strength in subjects accustomed to resistance training after 16 weeks of training at 80% of 1RM. Although a shorter training period of 9 weeks was used in the present study, comparable improvements (24%) were observed in the DAER training group. The 24% increase in elbow extensor strength of the DAER group was significantly greater than the 15% increase found in the DCER group.

Generally, greater increases in strength were noted for the elbow extensors than in the elbow flexors. Although the subjects participating in this study were previously trained, it is possible that they were more familiar with training the elbow flexors than the elbow extensors, particularly with the training exercises performed in this study. Consequently, the greater overall improvements in elbow extensor strength may be attributed to a learning effect (17) due to an initial unfamiliarity in performing the supine elbow extension exercise. However, this effect does not explain the greater increases in elbow extensor strength for the DAER group relative to the DCER group.

With the assumption that the magnitude of the training load is fundamental in augmenting strength, we hypothesized that DAER training relative to DCER training would produce significantly greater improvements in the strength of both muscle groups. This response was only observed in the elbow extensors. Clearly, the elbow flexors and elbow extensors responded differently to the same relative stimulus. An explanation for these results may be attributed to the intrinsic muscle fiber design of the elbow extensors. The elbow extensors are pennate muscles designed for the development of high force (13). In pennate muscles, muscle fibers attach at an angle, thereby increasing the effective CSA of the muscle (13). Conversely, the parallel-fiber design of the elbow flexors is not favorable for high force development (12). The high load (110–120% of concentric 1 RM) used under eccentric actions in the DAER training program may have exceeded the capacity of the elbow flexors and may have been better tolerated by the elbow extensors, accounting for the differences in the training response between the 2 muscle groups.

Prolonged periods of intense resistance training accompanied by training to muscle failure may produce overtraining (28) or ''neural fatigue'' (2), which are both detrimental to strength performance. Although the strength of the elbow flexors increased significantly in response to DAER training, the magnitude of the gains may have been compromised due to cumulative fatigue experienced during the frequent use of intense training loads for which the elbow flexors may not be well designed. The cumulative fatigue may have dampened the training effect by not allowing sufficient time for regeneration and ''supercompensation,'' which may explain the absence of a significantly greater improvement in the strength of the elbow flexors of the DAER group compared with the DCER group. Shorter periods of DAER training with an ''unloading'' phase may have elicited increases in elbow flexor strength similar to those elicited in the elbow extensors.

Although the number of repetitions performed by both training groups was within the proposed range for hypertrophy (14, 30), neither type of training induced a significant hypertrophic response in maximum (Table 2), proximal, midpoint, or distal CSA of the elbow flexors or extensors. In contrast to the findings of the present investigation, other studies using subjects of comparable training experience have reported significant hypertrophy in the upper extremity (13, 16, 23). However, the duration of these studies (10–16 weeks) was longer than the duration of the current study (9 weeks). Additionally, Hakkinen and colleagues (10) observed that hypertrophy of the leg extensors did not occur until the final 8 weeks of 16 weeks of high-intensity (concentric combined with eccentric actions) training.

In the present study, CSA was measured as the maximal CSA slice perpendicular to the length of the humerus. However, determination of maximum CSA of a muscle or muscle group depends on the orientation of the muscle fibers (24). As the triceps muscle group possesses a pennate design, the fibers are not arranged parallel with the humerus; thus, the perpendicular scan may not have provided a true indication of elbow extensor CSA. An increase in myofibrillar content could have occurred along the pennate orientation. Accordingly, hypertrophy of the elbow extensors may not have been detectable with the present method of CSA measurement. In contrast, Kawakami et al. (13) did observe a significant increase in the maximum CSA of the elbow extensors.

Our results (increases in elbow flexor and extensor strength without a concomitant increase in CSA) suggest that factors other than hypertrophy are responsible for the improvements in strength. Specific tension is a representation of the force-generating capacity per unit of muscle area, and any increases in specific tension are believed to be attributable to neural mechanisms (20, 21). Specific tension of the elbow flexors and extensors significantly increased in response to both types of training (Table 3). The differences between the magnitude of improvements elicited by DCER training and DAER training were not significant for either of the muscle groups trained.

A neural mechanism that may contribute to an increase in specific tension is a reduction in the coactivation of the antagonist muscle (6, 20). Coactivation of the antagonist is detrimental to the net torque in the intended direction of movement (26). Coactivation of the antagonist, through reciprocal inhibition, may impair complete activation of the agonist, leading to a further decrease in force production. By reducing the coactivation of the antagonist, more effective activation of the agonist is possible, resulting in greater force production without associated hypertrophy.

Training at high loads requires the recruitment of all or most motor units, as well as the need for all motor units to retain a high firing frequency (26). Because of the high training loads used during DAER training, recruitment and firing frequency of the motor units may have been greater than those during DCER training. Sale (26) has postulated that neural adaptations, such as the ability to increase the firing frequency of a motor unit, require an extended training period. Hakkinen et al. (11) demonstrated increases in electromyographic activity during 16 weeks of high-intensity resistance training (>80% of 1RM). Differences in specific tension of the elbow extensors of the DCER and DAER groups were approaching significance at the 9-week point. Thus, the training period of 9 weeks may not have been of sufficient duration to observe differences in specific tension improvements elicited by either type of training.

Muscle activation is also influenced by the duration of each muscle action. The training tempo for both the DAER and DCER training groups was controlled at 2 seconds per concentric action and 2 seconds per eccentric action for a total of 40 seconds per set. Evidence has indicated that during prolonged submaximal contractions, recruitment of previously inactive motor units occurs as activated motor units fatigue and no longer generate force (7). If the length of muscle action was sufficient to produce this effect, any advantage in the recruitment level maintained by DAER training load would have been lost, potentially accounting for the lack of difference between the 2 training protocols.

It was expected that 9 weeks of DAER training would produce greater improvements in strength, muscle CSA, and specific tension than would 9 weeks of DCER training. Elbow flexor and extensor strength increased in response to both training programs, but elbow extensor strength was significantly greater after DAER training. No changes in muscle CSA were observed in response to either training protocol. Improvements in specific tension were similar in both training groups. An increase in strength without a concomitant increase in muscle CSA suggests that much of the gain in strength was attributable to neurogenic factors. The difference between the DCER and DAER groups in the response of the elbow flexors and extensors may be related to differences in muscle architecture. The absence of significant muscle hypertrophy may reflect the trained status of the subjects and the relatively short duration of the training period.

Practical Applications

The following implications for resistance training can be drawn from this investigation:

- In training the elbow flexors, DCER training and DAER training are equally effective in developing strength.
- For some muscle groups, such as the elbow extensors, DAER training may be more effective than DCER training and may be worth the additional time and effort that is required by this form of training.
- It is unlikely that trained subjects will realize much increase in muscle CSA from DCER and DAER training during a 9-week training phase.

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