Eur J Appl Physiol (2003) 89: 578–586
DOI 10.1007/s00421-003-0842-2

ORIGINAL ARTICLE

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# The effects of eccentric and concentric training at different velocities on muscle hypertrophy

Accepted: 7 March 2003 / Published online: 17 May 2003

**Abstract** The purpose of this study was to examine the effect of isokinetic eccentric (ECC) and concentric (CON) training at two velocities [fast, 180° $s^{-1}$ (3.14 rad $s^{-1}$) and slow, 30° $s^{-1}$ (0.52 rad $s^{-1}$)] on muscle hypertrophy. Twenty-four untrained volunteers (age 18–36 years) participated in fast- ($n=13$) or slow- ($n=11$) velocity training, where they trained one arm eccentrically for 8 weeks followed by CON training of the opposite arm for 8 weeks. Ten subjects served as controls (CNT). Subjects were tested before and after training for elbow flexor muscle thickness by sonography and isokinetic strength (Biodex). Overall, ECC training resulted in greater hypertrophy than CON training ($P<0.01$). No significant strength or hypertrophy changes occurred in the CNT group. ECC (180° $s^{-1}$) training resulted in greater hypertrophy than CON (180° $s^{-1}$) training and CON (30° $s^{-1}$) training ($P<0.01$). ECC (30° $s^{-1}$) training resulted in greater hypertrophy than CON (180° $s^{-1}$) training ($P<0.05$), but not CON (30° $s^{-1}$) training. ECC (180° $s^{-1}$) training resulted in the greatest increases in strength ($P<0.01$). We conclude that ECC fast training is the most effective for muscle hypertrophy and strength gain.

**Keywords** Resistance training · Strength

## Introduction

Muscle hypertrophy is defined as an increase in muscle size, and is directly related to increased workload and tension development (Goldberg et al. 1975). Eccentric training has been shown to produce greater muscle hypertrophy than concentric training (Colliander and Tesch 1990; O'Hagan et al. 1995a; Higbie et al. 1996; Hortobágyi et al. 1996b; Seger et al. 1998), as a result of greater ability for maximal force generating capacity during eccentric contractions. In addition to greater hypertrophy, eccentric training protocols have also shown greater increases in strength than concentric training protocols (Duncan et al. 1989; Colliander and Tesch 1990; Higbie et al. 1996; Hortobágyi et al. 1996a,b, 1997). Given that force production is a determining factor for strength and muscle hypertrophy, and contractile force production varies with contraction velocity and type, it is surprising that very few studies have compared fast and slow contraction velocity training and its effect on muscle hypertrophy (Coyle et al. 1981) and strength (Paddon-Jones et al. 2001). Typically with concentric contractions, force output decreases exponentially with increasing contraction velocity (Wickiewicz et al. 1984; Sale et al. 1987; Hortobágyi and Katch 1990a; Westing et al. 1990, 1991). Conversely with eccentric contractions, force output will increase with increasing contraction velocity (Hortobágyi and Katch 1990a; Westing et al. 1990), although Westing et al. (1990) showed no significant changes beyond 60° $s^{-1}$. As contraction velocity decreases both eccentrically and concentrically, isometric contractions are mimicked, and the differences in force output are attenuated. Since the greatest difference in force production is seen when comparing high-velocity eccentric contractions with high-velocity concentric contractions (Hortobágyi and Katch 1990a; Westing et al. 1990), then the greatest differences in muscle hypertrophy and strength should be seen when comparing eccentric and concentric training at higher contraction velocities. Increases in strength and hypertrophy following either eccentric or concentric training at a fixed contraction velocity have been shown to parallel the force velocity relationship (Hortobáygi and Katch 1990b; Hortobáygi et al. 1996b, 1997; Seger et al. 1998), but no study has

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compared eccentric and concentric training at two different contraction velocities simultaneously.

The purpose of the present investigation was to compare both eccentric and concentric training at high and low contraction velocity to determine if the force output difference between high and low velocity within a given contraction type will affect muscle hypertrophy and strength. As force production has been theorized to be a determinant of muscle hypertrophy and strength gain, we hypothesized that eccentric training would produce greater hypertrophy than concentric training, and that the greatest difference in muscle hypertrophy would be seen when comparing high-velocity eccentric training and high-velocity concentric training.

## Methods

### Design

The experiment was broken up into two 8-week strength-training phases (one for each arm) separated by a 5-week washout phase where no training took place. As a result, there were four different testing points—pre- and post-testing for phase I and pre and post-testing for phase II. Phase I of the experiment included only eccentric training of the elbow flexors of one arm (randomized) while phase II included only concentric training on the opposite arm. The subjects in this study were included in a study of the effects of cross-education (increases in strength of the untrained limb) following eccentric training (Farthing and Chilibeck 2003). Therefore the purpose of the washout phase was to attenuate the effect of cross-education on the subsequent training of the opposite arm. Prior to the start of phase I, the subjects were randomized into either a fast or slow training group (as determined by contraction velocity) where they would remain for the duration of the experiment. A control group was also included in the experiment but they were designated as controls before the training subjects were randomized into either group. Thus, the control group was not randomly assigned. The study design is illustrated in Fig. 1.

### Subjects

Thirty-six volunteers (13 male, 23 female) with little strength training experience participated in the study. Twenty-six subjects were randomized to groups that trained at either a fast velocity [180° $s^{-1}$ (3.14 rad $s^{-1}$)] (four male, nine female) or a slow velocity [30° $s^{-1}$ (0.52 rad $s^{-1}$)] (seven male, six female) of the elbow flexors, while ten subjects (two male, eight female) served as non-training controls. The subjects were once again randomized to train either their right arm or their left arm in phase I, and hence the opposite arm in phase II. Subject characteristics are presented in Table 1. Any potential volunteers who were currently strength training their upper body were screened from participation in the study. Both males and females were included in the experiment since studies have shown no difference between untrained males and females in their relative increase in muscle hypertrophy and strength following a period of resistance training (Cureton et al. 1988; Davies et al. 1988; Staron et al. 1994; O'Hagen et al. 1995b; Abe et al. 2000; Candow et al. 2001). All subjects provided informed written consent and the study was approved by the University of Saskatchewan Ethics Review Board for Research in Humans.

### Strength measures

One week after the recruitment process, each subject was required to attend a laboratory familiarization session to lessen any effect of learning during subsequent strength testing. During this session, each participant completed one or two eccentric and concentric contractions on a Biodex isokinetic dynamometer (Biodex System 3, Biodex Medical Systems, Shirley, N.Y.) at each velocity (30° $s^{-1}$ and 180° $s^{-1}$).

Before and after training, the arm strength testing protocol was completed over 2 successive days. On day 1, all participants tested their right arm, and on day 2 they tested their left arm. Right and left arm eccentric and concentric peak torque measures were assessed using a Biodex isokinetic dynamometer set up for elbow flexion/extension in the concentric/eccentric mode using System 3 computer Software.

Each subject was required to complete four separate testing conditions, in random order, on each arm: (1) eccentric fast (180° $s^{-1}$); (2) eccentric slow (30° $s^{-1}$); (3) concentric fast (180° $s^{-1}$); (4) concentric slow (30° $s^{-1}$). The elbow flexion/extension attachment on the dynamometer was set to 100° range of motion, so that arm movement was approximately from 60° to 160° elbow extension for eccentric contractions and from 160° to 60° elbow extension for concentric contractions. Each testing condition consisted of three maximal repetitions, separated by 1 min rest, of which the highest peak torque value was recorded. Following the testing contractions, the arm was passively moved back to the starting position. The torque measures were corrected for the effects of gravity on the lever arm and the handle of the dynamometer, and for each subject's individual limb weight.

The Biodex chair was set to produce an angle of 85° of hip flexion. The back of the upper arm being tested was supported by an arm pad and the dynamometer was rotated 30° outward from the chair. The lever arm attachment length, chair back, and arm pad height were adjusted so that the rotational axis of the dynamometer was positioned to be coaxial with the elbow axis (lateral epicondyle) during testing. Stabilization belts were fastened across the lap and across the chest, and a Velcro arm strap was secured around the upper arm to keep the back of the arm against the arm pad and the elbow axis of rotation in the correct position. For each subject, the individual chair and dynamometer settings used during testing were replicated during the training program.

Reproducibility of the tests for torque measurement was assessed on nine subjects (two male and seven female) on 2 separate days. For the concentric torque measurements at 30° $s^{-1}$ and 180° $s^{-1}$ the coefficients of variation were 3.6% and 7.3%, respec-

**Fig. 1** Illustration of the study design

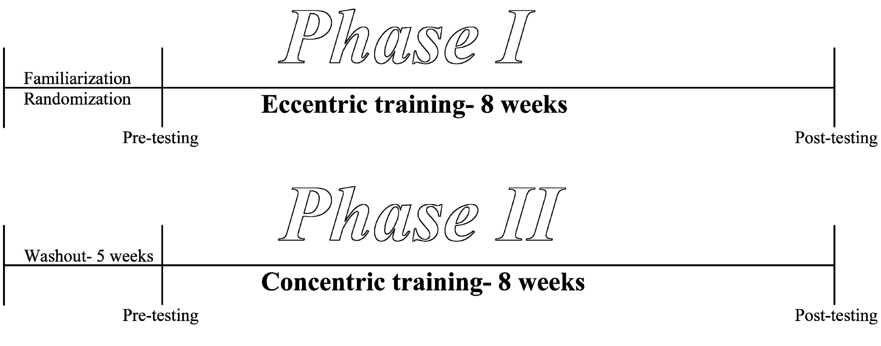

**Table 1** Group descriptions for subjects who completed both training phases. All values are means (SEM)

| | Fast group ($n=4$ males, 9 females) | Slow group ($n=7$ males, 4 females) | Control group ($n=2$ males, 8 females) |
|---|---|---|---|
| Age (years) | 21.9 (1.5) | 19.6 (0.7) | 22.7 (0.9) |
| Height (cm) | 167.1 (2.2) | 175.7 (2.3)* | 168.8 (2.6) |
| Body mass (kg) | 65.6 (3.8) | 74.6 (3.5) | 65.2 (3.2) |
| Strength training experience in previous year (months) | 1.2 (0.6) | 2.7 (1.1) | 2.3 (1.1) |

(*Value for slow-training group significantly greater than that for fast-training group ($P<0.05$).

tively, and the test–retest correlation coefficients were 0.99 and 0.98, respectively. For the eccentric torque measurements at $30^\circ\ \mathrm{s}^{-1}$ and $180^\circ\ \mathrm{s}^{-1}$ the coefficients of variation were 5.7% and 7.1%, respectively, and the test–retest correlation coefficients were 0.99 and 0.97, respectively.

### Muscle thickness measures

Elbow flexor muscle thickness measures were performed before and after training on the day prior to any strength measures. Measurements were taken 5–7 days after the last training session to prevent any swelling in response to the last training session from contributing to the muscle thickness measurement. Elbow flexor muscle thickness was measured using B-Mode ultrasound (Aloka SSD-500, Tokyo, Japan). A small mark was drawn on the lateral side of the arm to indicate exactly two-thirds of the distance down from the acromion process to the olecranon process. A tape measure was then wrapped around the arm at the two-thirds mark and used to mark another reference point on the bulk of the biceps, where the center of the ultrasound probe would be placed.

Once the reference points were taken each subject laid their arm flat down on a tabletop with their biceps facing upwards and forearm supinated. Great care was taken using overhead transparency film and markings on the skin to ensure that identical sites were measured on each occasion.

A water-soluble transmission gel was applied to the measurement site and a 5-MHz ultrasound probe rested on the biceps. Once the researcher was satisfied with the quality of the image produced, the image on the monitor was frozen. With the image frozen, a cursor could be enabled in order to measure the thickness of the elbow flexors (centimeters) at three sites—the proximal site, the mid site, and the distal site, as determined by the divisions (1 cm) on the monitor. The distal and proximal sites on the monitor were 6 cm apart with the mid site located equidistant between them. The mid site would correspond to where the reference mark was drawn on the bulk of the biceps.

The muscle thickness measurement was extracted from the monitor image using a method similar to that described by Abe et al. (2000), with the distance from the subcutaneous adipose layer to the surface of the humerus bone taken as elbow flexor muscle thickness. Three muscle thickness measurements were taken at each of three sites. The two values closest to each other were then taken and averaged to achieve a final muscle thickness value for that site. If the two closest values could not be determined by the previous three measurements (i.e. high and low values were the same distance from the middle value), then a fourth measurement was performed.

Reproducibility of measurements of muscle thickness was determined on 2 separate days for ten subjects (six males and four females). For the distal, mid, and proximal sites of the elbow flexors, the coefficients of variation were 1.8%, 1.8%, and 2.6%, and the test–retest correlation coefficients were 0.98, 0.98, and 0.95, respectively.

### Resistance training program

The resistance training program was identical for both phases of the study, with the exception that in phase I only eccentric repetitions were performed, while in phase II only concentric repetitions were performed. Since both arms of each subject were used for comparison, a 5-week washout phase was included in the experiment to help alleviate the effect that cross-education (Stromberg 1986) might have on the results in phase II. The elbow flexors strength-training program began on the week following the testing. The subjects trained their elbow flexors under full supervision on the Biodex isokinetic dynamometer three times per week for 8 weeks for a total of 24 training sessions at their assigned training velocity (either $30^\circ\ \mathrm{s}^{-1}$ or $180^\circ\ \mathrm{s}^{-1}$). The subjects were not eligible to post-test until all 24 training sessions were completed to ensure that every subject was exposed to exactly the same training volume (total sets × total repetitions) prior to post-testing. Because our main purpose was to evaluate the effects of training on muscle hypertrophy, we chose the duration of 8 weeks, as this is a time period that has previously been observed to be sufficient for significant muscle hypertrophy. Specifically, elbow flexor muscle thickness is significantly increased after 4 and 8 weeks of resistance training in men and women, respectively, when training frequency is 3 days per week (Abe et al. 2000).

The training program involved a progressive increase from two to six sets of eight maximal repetitions per training session over the first 13 training sessions, six sets for training sessions 13–22 and a taper down to three sets of eight maximal repetitions prior to post-testing (training sessions 23 and 24). The taper was included in the program because it has been shown to result in significantly higher post-test maximal voluntary contractions following an elbow flexor strength training protocol (Gibala et al. 1994). One minute of rest was given between sets.

### Statistical analysis

Muscle hypertrophy and strength could be analyzed at the completion of both training phases when each subject had trained both arms: one eccentrically and one concentrically. The control group arms were randomized at the end of each phase so that one arm (dominant or non-dominant) was compared to the training groups' eccentrically trained arm at the end of the first 8-week period (phase I), and the opposite arm was compared to the training groups' concentrically trained arm at the end of the second 8-week period (phase II). In order to simplify the data and represent it in terms of relative change, percent change muscle thickness and strength scores were used as the dependent variable in our analyses. To detect differences in baseline measures between groups, pre-test scores were analyzed by a one-way analysis of variance (ANOVA).

Muscle hypertrophy was analyzed by a 3×2 (group × arm) ANOVA with repeated measures on the second factor for each of the proximal, mid, and distal sites, using muscle thickness change scores as the dependent variable.

The changes in strength (torque), rate of torque development (defined as peak torque divided by time to reach peak torque), and the joint angle corresponding to peak torque for each contraction type (eccentric and concentric) were analyzed by a 3×2×2 (group × arm × velocity) ANOVA with repeated measures on the last two factors. Pre-test strength scores for each testing condition (subjects pooled) were analyzed by a 2×2 (contraction type × velocity) ANOVA to determine the torque–velocity relationship.

Statistical significance was set at $P \le 0.05$. In all cases, if significant main effects or interactions were found, Tukey's HSD test was used for post hoc comparison of means.

## Results

### Subjects

Thirty-four subjects completed the testing at the end of phase II. Two subjects in the slow training group dropped out after phase I due to lack of time for training. All 34 subjects were included in the muscle thickness analysis, while 32 were included for the strength analysis. Two subjects could not complete the strength testing due to illness. There were no significant differences between groups for age, body mass, and resistance training experience (Table 1). However, the slow-training group subjects were significantly taller than the fast-training group subjects (Table 1; $P < 0.05$). Since subjects were randomly assigned to the training groups, these differences can be attributed to chance. For the subjects that completed both phases of training, there were no differences at baseline between groups for any torque or muscle thickness measures. Prior to training, our subject pool displayed a similar torque–velocity relationship (Fig. 2) as has been previously documented for the elbow flexors (Sale et al. 1987; Hortobágyi and Katch 1990a).

### Muscle thickness

#### *Proximal site*

The change in muscle thickness at the proximal site revealed a significant arm effect ($P < 0.05$) and group effect ($P < 0.01$), indicating that overall the eccentrically trained arm showed a greater change in muscle thickness than the concentrically trained arm, and that the fast- and slow-training groups showed a greater change in muscle thickness than the control group ($P < 0.01$ and $P < 0.05$, respectively; Fig. 3). The group × arm interaction approached significance ($P = 0.066$).

#### *Mid site*

The change in muscle thickness at the mid site revealed a significant group × arm interaction ($P < 0.01$; Fig. 3). Post hoc analyses revealed that the fast eccentrically trained arm showed a greater change in muscle thickness than the fast concentrically trained arm ($P < 0.01$), the slow concentrically trained arm ($P < 0.05$), the designated control eccentric arm ($P < 0.01$), and the designated control concentric arm ($P < 0.01$). The change in muscle thickness in the slow eccentrically trained arm

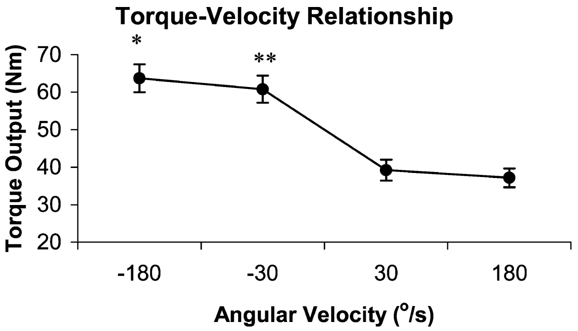

**Fig. 2** The torque–velocity relationship for the elbow flexors muscle group. Negative angular velocities indicate eccentric contractions, and positive angular velocities indicate concentric contractions. *Torque for the eccentric fast condition ($180° s^{-1}$) was significantly greater than all other testing conditions ($P < 0.05$). **Torque for the eccentric slow condition ($30° s^{-1}$) was significantly greater than both concentric testing conditions ($P < 0.05$). The concentric slow condition ($30° s^{-1}$) was not significantly greater than the concentric fast condition ($180° s^{-1}$) ($P = 0.082$). All values are means (SEM)

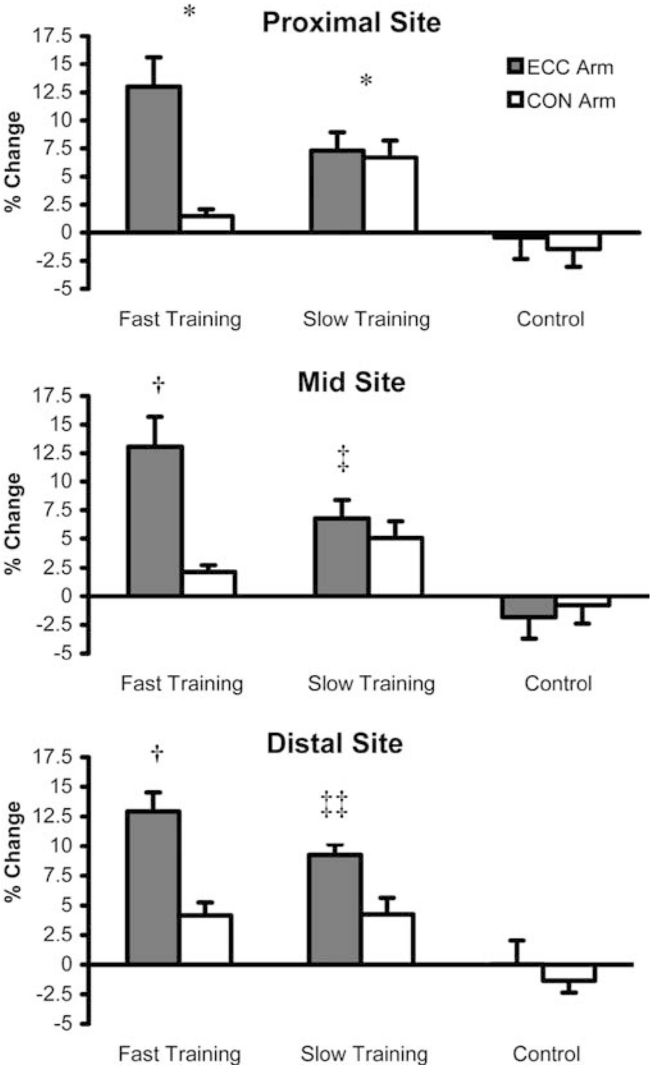

**Fig. 3** Proximal, mid, and distal muscle thickness percent changes across groups (data for two arms per group—eccentric and concentric). *Eccentric and concentric arms combined significantly greater than control group arms ($P < 0.01$). †Significantly greater than all except the eccentric arm from the slow training group ($P < 0.01$). ‡Significantly greater than the designated control eccentric arm ($P < 0.01$). ‡‡Significantly greater than both control group arms ($P < 0.01$). All values are means (SEM)

was greater than the designated control eccentric arm ($P < 0.05$). Neither the fast nor slow concentrically trained arms showed a significantly greater change in muscle thickness than either control arm.

### *Distal site*

The change in muscle thickness at the distal site revealed a significant group × arm interaction ($P < 0.05$; Figure 3). Similar to the mid site, post hoc analyses revealed that the fast eccentrically trained arm showed a greater change in muscle thickness than the fast concentrically trained arm ($P < 0.01$), the slow concentrically trained arm ($P < 0.01$), the designated control eccentric arm ($P < 0.01$), and the designated control concentric arm ($P < 0.01$). The change in muscle thickness in the slow eccentrically trained arm was significantly greater than both the designated control eccentric ($P < 0.01$) and concentric ($P < 0.01$) arms. Similar to the mid site, both concentrically trained arms did not show a significantly greater change in muscle thickness than either control arm.

### *Combined sites*

Eccentric fast training resulted in greater overall (all three sites) muscle thickness change [mean (SEM) 13% (2.5)] than concentric slow [5.3% (1.5)] ($P < 0.05$) and concentric fast [2.6% (0.7)] ($P < 0.01$) training, and both control group arms [−0.8% (1.8) and −1.2% (1.6)] ($P < 0.01$). Eccentric slow [7.8% (1.3)] training was significantly greater than both control group arms ($P < 0.05$).

## Torque

Typical torque tracings before and after training are shown in Fig. 4. Peak torque at the two testing velocities (30° $s^{-1}$ and 180° $s^{-1}$), before and after eccentric and concentric training are presented for all groups in Fig. 5. For the change in eccentric torque, there was a significant group × arm interaction ($P < 0.01$). Training at fast eccentric velocity was the most beneficial for increasing eccentric torque (across the two testing velocities). Post hoc analyses revealed that the change in eccentric torque for the fast-training group after eccentric training was significantly greater than all other groups ($P < 0.05$). The change in eccentric torque for the slow-training group after eccentric or concentric training was significantly greater than the change in the designated concentric control group arm ($P < 0.05$).

For the change in concentric torque, there was a significant group × arm interaction ($P < 0.05$). Training at fast eccentric velocity was most beneficial for increasing concentric torque (across the two testing velocities). Post hoc analyses indicated that the change in concentric torque for the fast-training group after eccentric training was significantly greater than all other groups, except the slow group after eccentric training ($P < 0.05$). The change in concentric torque for the slow-training group after eccentric training was significantly greater than the change for the designated concentric control group arm ($P < 0.05$).

## Changes in rate of torque development and angle of peak torque

There were no differences between groups over the training program for rates of torque development or angle of peak torque during eccentric or concentric testing at 30° $s^{-1}$ and 180° $s^{-1}$, with the exception that there was a significant group × velocity interaction ($P < 0.05$) for change in angle of peak torque during concentric contractions. Post hoc analyses indicated that the fast-trained group produced peak torque at a joint angle which was 11° later in the range of movement (when comparing post- to pre-training measures) during concentric testing at 30° $s^{-1}$. This was significantly different from the slow-training group, which produced peak torque at a joint angle which as 8° earlier in the range of movement (when comparing post- to pre-training measures) during concentric testing at 30° $s^{-1}$ ($P < 0.01$).

## Discussion

The major finding of this study is that high-velocity (180° $s^{-1}$) eccentric training is the most effective for increasing muscle hypertrophy in the elbow flexors. Further, when all velocities were combined, eccentric training was more effective than concentric training for increasing muscle hypertrophy. The latter is supported by several studies comparing the effectiveness of eccentric and concentric training for muscle hypertrophy (Higbie et al. 1996; Hortobáygi et al. 1996b; Seger et al. 1998).

In our experiment, only eccentric training resulted in significant muscle hypertrophy, but in all cases there was a trend for concentric training to be greater than the controls (Fig. 3). This is consistent with two previous studies comparing eccentric and concentric training, which reported significant muscle hypertrophy only after eccentric training (Hortobáygi et al. 1996b; Seger et al. 1998). However, one study comparing fast and slow concentric training and muscle hypertrophy found that only the fast concentric (300° $s^{-1}$) training group significantly increased type II muscle fiber area by 11% (Coyle et al. 1981). Their results may be limited by the fact that the variation inherent in the measurements from muscle biopsy samples is quite large (Bromstrand and Ekblom 1982), and perhaps greater than the 11% difference they reported between pre- and post-training (Coyle et al. 1981). Several other studies have also reported significant hypertrophy after concentric

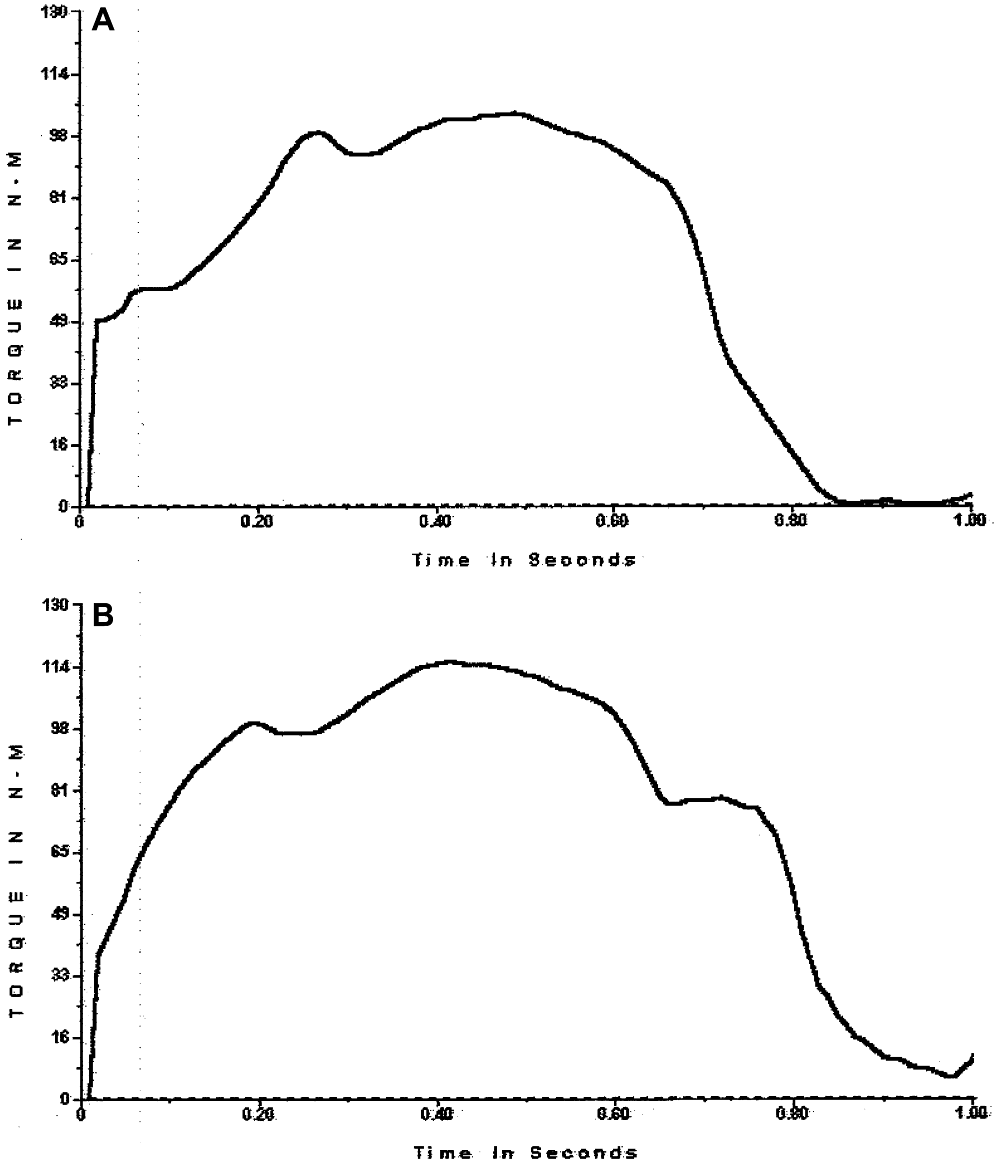

**Fig. 4A, B** Force traces from an individual in the fast-training group. The tracings show eccentric torque at 180° $s^{-1}$ in the trained elbow flexors (**A**) before and (**B**) after eight weeks of eccentric training

training (Housh et al. 1992; O'Hagan et al. 1995a; Higbie et al. 1996), but variations in training duration and volume, and muscle group make it difficult to directly compare with our results. O'Hagan et al. (1995a) also trained the elbow flexors but imparted a much longer training duration (20 weeks), while other studies have applied more similar training durations, but with a greater training volume per session (Coyle et al. 1981; Housh et al. 1992).

The major finding in our study that fast-velocity eccentric training is the most effective for muscle hypertrophy is difficult to contrast with earlier research since the effect of high and low contraction velocity training on muscle hypertrophy has not previously been examined. A recent study reported a significant increase in the percentage of type IIb muscle fibers in the elbow flexors after fast-velocity (180° $s^{-1}$) eccentric training, whereas no significant changes were observed after slow-velocity (30° $s^{-1}$) eccentric training (Paddon-Jones et al. 2001). It is possible that the increase in type IIb muscle fiber percentage after fast eccentric training may have been coupled with greater muscle hypertrophy of these fibers, but muscle fiber area was not reported. Other studies have measured muscle hypertrophy after isokinetic eccentric and concentric training, but have not used a training velocity higher than 90° $s^{-1}$ and did not compare two different training velocities (Seger et al. 1998; Higbie et al. 1996; Hortobáygi et al. 1996b). Combining our results and previous work, it appears that as training velocity increases, the observed difference in muscle hypertrophy between eccentric and concentric training is exaggerated.

A mechanism for greater muscle hypertrophy after eccentric training is likely to be related to an increased level of muscle fiber damage and protein degradation (Fridén et al. 1983; Stauber et al. 1990; Enoka 1996),

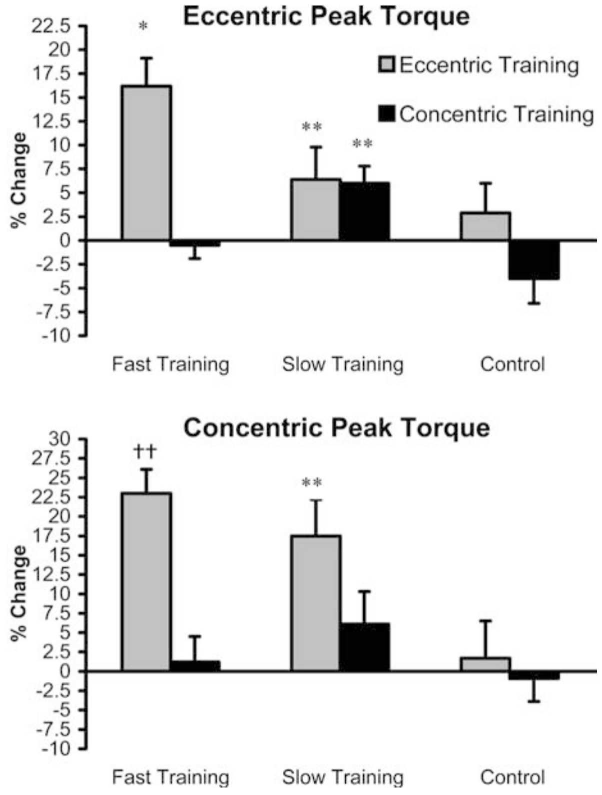

**Fig. 5** Peak torque percent changes (collapsed across testing velocities) after eccentric and concentric training at the fast and slow velocities (180° $s^{-1}$ and 30° $s^{-1}$). *Significantly greater than all other training conditions across groups ($P < 0.05$). **Significantly greater than the control group after the concentric training phase ($P < 0.05$). ††Significantly greater than all other conditions except for the slow eccentric training condition ($P < 0.05$)

which will result in greater satellite cell infiltration and a greater repair response. The muscle damage associated with eccentric contractions is likely to be caused by muscle cross-bridge disruptions resulting from high force contractions combined with muscle lengthening (Stauber 1989; Gibala et al. 1995; Behm 1995; Enoka 1996; Stupka et al. 2001). Greater force production during eccentric than concentric contractions has been proposed as the precursor for more muscle damage, and hence more hypertrophy (Behm 1995). In our study the muscle hypertrophy results (Fig. 3) mimicked the torque–velocity relationship in that fast eccentric training showed the greatest hypertrophy, followed by slow eccentric, slow concentric, and fast concentric. In concordance with our hypothesis, which was based on the theory that greater force production would lead to greater muscle hypertrophy, the largest difference in muscle hypertrophy was shown between the fast eccentric arm and the fast concentric arm of the training groups (Fig. 3). Our results provide evidence that force level during contraction is a determinant of muscle hypertrophy.

In our study, the finding that eccentric training produced greater strength increases than concentric training is consistent with previous research (Duncan et al. 1989; Colliander and Tesch 1990; Higbie et al. 1996; Hortobágyi et al. 1996a, b, 1997). In our experiment, fast eccentric training resulted in the greatest increases in eccentric torque, while fast and slow eccentric training were most beneficial for increasing concentric torque (Fig. 5). Fast eccentric training also resulted in the greatest muscle hypertrophy (Fig. 3), which is not surprising since previous research has shown a strong relationship between the size of a muscle and its strength (Maughan et al. 1983; Sale et al. 1987).

Interestingly, there was little evidence in our study to support training specificity to contraction type. While fast eccentric training was most beneficial for increasing eccentric torque, there was no difference between slow eccentric and slow concentric training for changes in eccentric torque. Also, eccentric training at either velocity was superior to concentric training for increasing concentric torque (Fig. 5). There was also little evidence for specificity to velocity as there were no group × velocity interactions for change in torque (Fig. 5). High-velocity training has shown less specificity for strength than low-velocity training in the past (Coyle et al. 1981; Bell et al. 1992), especially eccentrically (Duncan et al. 1989; Ryan et al. 1991; Paddon-Jones et al. 2001), but specificity of contraction type has been repeatedly shown in previous studies (Tomberlin et al. 1991; Higbie et al. 1996; Hortobáygi et al. 1996a,b, 1997). The studies that reported specificity to contraction type all used training velocities lower than our training velocity (180° $s^{-1}$). In concordance with our findings, one other study has reported no contraction type specificity after eccentric training with high- versus low-velocity eccentric training (Paddon-Jones et al. 2001).

In general, the observed increases in torque with training could not be attributed to increases in rates of force development or changes in the angle of peak torque development with training. Some individuals had higher rates of torque development following training, which meant that peak torque occurred earlier in the range of motion, while others had similar or slower rates of torque development accompanying an increased torque following training, which meant that peak torque occurred later in the range of motion. Across groups, this resulted in non-significant changes in rates of torque development and angle of peak torque development. The only exception was that training at fast velocities resulted in a shift to an angle of peak concentric torque development that was later in the range of motion, while training at slow velocities resulted in a shift to an angle of peak concentric torque development that was earlier in the range of motion during strength testing at slow velocities. These changes, while significant, were quite minor (i.e. the shift in angle of peak torque development was only by 8–11° in a range of movement that covered 100°).

One final finding that deserves comment was that at baseline, concentric peak torque at 30° $s^{-1}$ was not significantly greater than peak torque at 180° $s^{-1}$ (Fig. 2). In addition to the current study, there are others that show no differences in peak torque with increasing velocity of concentric elbow flexion in untrained subjects (Sale et al. 1987; Hortobágyi and Katch 1990a). It is possible that untrained individuals, such as those of the current study, are unable to fully activate their elbow flexors at lower velocities of contraction.

We conclude that fast-velocity eccentric isokinetic training is more effective than slow eccentric, slow concentric, and fast concentric isokinetic training for muscle hypertrophy and increasing strength. We also conclude that overall, eccentric isokinetic training is more effective than concentric isokinetic training for strength development and muscle hypertrophy.

**Acknowledgements** We gratefully acknowledge the subjects who dedicated a great deal of time to participate in this study. We also acknowledge the technical assistance of Doug Jacobson. Jonathan Farthing is supported by a scholarship from The Natural Sciences and Engineering Research Council of Canada. The experiments described in this paper comply with the current laws of Canada.

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