Effect of time of concentric muscle actions on strength, hypertrophy, and specific tension in resistance-trained women

by

Ellen Maureen Gillies
B.Sc., University of Regina, 1983

A Thesis Submitted in Partial Fulfillment of the
Requirements for the Degree of
MASTER OF SCIENCE

in the School of Physical Education

We accept this thesis as conforming to the required standard

[redacted]

Dr. D. Docherty, Supervisor (School of Physical Education)

[redacted]

Dr. C.A. Gaul, Department Member (School of Physical Education)

[redacted]

Dr. D. Paul, Outside Member (Department of Biology)

[redacted]

Dr. P. Neary (External Examiner)

University of Victoria

Supervisor: Dr. D. Docherty

ABSTRACT

The study investigated the effects of different concentric muscle action times during resistance training on neuromuscular changes. Eccentric muscle action time was 2 s for both groups while the concentric phases were 8 s for the Super Slow (SS) group and 2 s for the Controlled Tempo (CT) group. 21 resistance-trained women volunteered to participate and were randomly assigned to either the SS group (n = 13, age 28.6 +/- 5.5 [SD]) or the CT group (n = 8, age 26.3 +/- 9.3). Training was conducted 3 times per week for 8 weeks with 2 sets (SS) or 4 sets (CT) of 8-10 RM using free weights to exercise the elbow flexors and extensors. 1 RM strength, 8 RM strength , relaxed and flexed arm girths, and skinfolds were measured at 0, 4, and 8 weeks. Muscle cross-sectional area (CSA), evaluated using magnetic resonance imagery, and specific tension (kg/cm^2), were measured at 0 and 8 weeks. The SS and CT training protocols elicited significant and similar increases in flexor and extensor 1 RM strength at Weeks 4 and 8 ($p < .01$). Both groups had significant increases in 8 RM flexor and extensor strength at Week 4 ($p < .01$), while only the SS group had significant increases at Week 8 ($p < .01$). Arm girths increased significantly ($p < .01$) in both groups at Week 4, while only the SS group had significant ($p < .05$) increases at Week 8. Extensor CSA increased significantly ($p < .05$) in both groups, while only the SS group had significant ($p < .01$) increases in flexor CSA. The groups had significant increases in specific tension of both muscle groups at Week 8 ($p < .05$). In conclusion, two sets of resistance training exercises performed with a slow concentric phase were as effective as 4 sets performed

more quickly, in producing increases in strength, muscle cross-sectional area, and specific tension in resistance-trained women.

Examiners:

[redacted]

Dr. D. Docherty, Supervisor (School of Physical Education)

[redacted]

Dr. C.A. Gaul, Department Member (School of Physical Education)

[redacted]

Dr. D. Paul, Outside Member (Department of Biology)

[redacted]

Dr. P. Neary (External Examiner)

TABLE OF CONTENTS

List of Tables

List of Figures

Acknowlegements

I would like to thank my supervisor, Dr. Dave Docherty, for his help in the preparation of this thesis, especially for always making time to talk to me, and for his promptness in returning various versions of this thesis. I would also like to thank my other committee members, Drs. Gaul, Paul, and Neary, for their comments.

A major portion of my research would not have been possible without the cooperation of Dr. Mitten and the Victoria General Hospital. A huge thanks to MRI technician Rob Calland for coming in on his days off and always being helpful.

I would like to thank Kirsten Lane for doing the anthropometric measurements and always being very accommodating to the time schedule of this study.

Finally, I would like to thank all the women who participated in this study for their enthusiasm and commitment to the training program, and the effort that they exerted throughout training.

Dedication

To Tommy (one of the magnificent seven)

- and your future.

Introduction

Resistance training is performed for a variety of reasons including health, rehabilitation following injury, personal fitness, body aesthetics, or as a component of a training program for high performance athletes. Changes resulting from resistance training can be an increased expression of force and muscle hypertrophy. There is a strong positive relationship between muscle cross-sectional area (CSA) and force production (Ikai & Fukunaga, 1968; Maughan, Watson, & Weir, 1983; Moritani, 1992; Ryushi, Fukunagi, Hakkinen, & Kaunamen, 1988; Tesch, 1992) with increases in muscle CSA directly related to the degree of muscle hypertrophy (Sale, 1988).

Strength gains in the early stages of a resistance training program often occur without structural changes in muscle and have been attributed to neural factors (Enoka, 1988; Moritani & deVries, 1979; Sale, 1988), especially learning and coordination (Rutherford & Jones, 1986). Neural changes can be quantified through an increase in electromyographic (EMG) recordings or changes in specific tension, which is the amount of force produced per unit of muscle CSA. Morphological changes, especially hypertrophy in the CSA of the individual muscle fibers, begin to play a major role in strength development as training continues (Ikai & Fukanaga, 1970; McDonagh & Davies, 1984; Komi, 1986).

Acute neural responses to time under tension, evaluated by electromyography, include increased electrical muscle activity and motor unit recruitment occurring throughout sustained submaximal voluntary contractions (Fuglevand, Zackowski, Huey, & Enoka, 1991; Garland, Enoka, Serrano, & Robinson, 1994; Maton, 1981; Stephens & Taylor, 1971; Wittekopf, Schaaf, & Taubenheim, 1986). The role of these acute responses on chronic changes, such as hypertrophy, remains to be clarified.

Tension is an important stimulus for hypertrophy because muscle CSA increases in response to tension (Goldberg, Etlinger, Goldspink, & Jablecki, 1975), even passive tension (Barnett, Holly, & Ashmore, 1980) or tension applied with no influence from neural or blood flow factors (Buresova, Gutmann, & Klicpera, 1969). A "high degree" of muscle tension is a necessary stimulus for hypertrophy, whereas muscle actions of low force or tension development do not stimulate muscle growth (Mikesky, Matthews, Giddings, & Gonyea, 1989; Sale & MacDougall, 1981) and produce small increases in maximum strength (Anderson & Kearney, 1982; Dons, Bollerup, Bonde-Petersen, & Hancke, 1979).

Indirect evidence for increasing the time under tension of individual muscle actions as a stimulus for hypertrophy comes from the change in force throughout a free-weight lift (Atha, 1981) with about half of the lift time spent decelerating the load (Hay, Andrews, & Vaughan, 1980: Wilson, 1994). It has been suggested that slow training can decrease the role of momentum and produce tension in the target muscles for a longer period of time and thereby, provide a greater stimulus for strength development (Poliquin, 1990; Westcott, 1989).

The role of the time that the muscles are under tension in hypertrophy and strength development remains relatively undefined. Few studies have actually examined time under tension as an independent variable using free-weights with repetitions and sets within the range identified to produce hypertrophy. The studies that have varied time under tension between groups have used approximately 2 seconds or less for all groups (Harmon, Morrissey, Frykman, & Han, 1990; Palmieri, 1987), or have used an unspecified time such as "fast as possible" and "always controlled" (Young & Bilby, 1991). Similar increases in maximum strength were found in these studies. Only Young and Bilby assessed hypertrophy and found no significant difference between the groups. There have been no studies using free weights which have examined the effects of periods of time under tension of durations longer than 2 seconds.

Studies which have used an isokinetic training mode have varied time under tension as an independent variable. The purpose of most of these studies has been to examine the effect of various training velocities on peak torque development (Caiozzo, Perrine, & Edgerton, 1981; Coyle & Feiring, 1980; Ewing, Wolfe, Rodgers, Amundson, & Stull, 1990; Katch, Pechar, Pardew, & Smith, 1975; Moffroid & Whipple, 1970). Of those studies that have trained with velocities such that the time to complete the muscle action was 2 seconds or more, the increases have tended to be larger for the slower training group (Katch, Pechar, Pardew, & Smith; Moffroid & Whipple; Van Oteghen, 1975). Only Van Oteghen statistically analyzed the strength changes between groups and reported that only the slow training group (4 s versus 2 s for the fast group) improved strength significantly over a control group.

There is a lack of information regarding the effects of time under tension on strength and hypertrophy development and consequently there is a need to develop a better understanding of the role time under tension has on strength and hypertrophy. The purpose of this study was to compare the effects of two resistance training programs which involved different times under concentric tension and initially equated for training volume, on muscular strength, hypertrophy, and specific tension in resistance-trained women. A secondary purpose was to examine the time course of training induced changes.

Statement of the Problem

There were three major research problems addressed in this study:

1. To identify the effects of an 8 week, 8 RM resistance training program (4 sets of 8 repetitions with a concentric:eccentric muscle action ratio of 2 s:2 s) on muscle CSA, strength performance, specific tension, and anthropometric measures on elbow flexors and extensors in trained subjects.

Specific Objectives

- to identify the effects of this program on muscle CSA
- to identify the effects of this program on 1 RM and 8 RM strength
- to identify the effects of this program on specific tension
- to identify the effects of this program on the rate of change in 1 RM and 8 RM strength
- to identify the effects of this program on the rate of change in training volume
- to identify the effects of this program on flexed girth, relaxed girth, and sum of skinfolds

2. To identify the effects of an 8 week, 8 RM resistance training program (2 sets of 8 repetitions with a concentric:eccentric muscle action ratio of 8 s:2 s) on muscle CSA, strength performance, specific tension, and anthropometric measures on elbow flexors and extensors in trained subjects.

Specific Objectives

- to identify the effects of this program on muscle CSA
- to identify the effects of this program on 1 RM and 8 RM strength

- to identify the effects of this program on specific tension
- to identify the effects of this program on the rate of change in 1 RM and 8 RM strength
- to identify the effects of this program on the rate of change in training volume
- to identify the effects of this program on flexed girth, relaxed girth, and sum of skinfolds

3. To determine if the two 8 week training protocols produced significant differences in muscle CSA, strength performance, specific tension, and anthropometric measures on elbow flexors and extensors in trained subjects.

Specific Objectives

- to determine if there was a significant difference between the effects of these programs on muscle cross-sectional area
- to determine if there was a significant difference between the effects of these programs on 1 RM and 8 RM strength
- to determine if there was a significant difference between the effects of these programs on specific tension
- to determine if there was a significant difference between the effects of these programs on the rate of change in 1 RM and 8 RM strength
- to determine if there was a significant difference between the effects of these programs on the rate of change in training volume
- to determine if there was a significant difference between the effects of these programs on flexed girth, relaxed girth, and sum of skinfolds

Hypotheses

The following null hypotheses were tested:

Ho 1: The 8 week training program will have no significant effect on muscle cross-sectional area (CSA) on the following muscle groups of the two training groups:

Ho 1a: elbow flexors

Ho 1b: elbow extensors

Ho 2: The 8 week training program will have no significant effect on the following strength variables of the two training groups:

Ho 2a: 1 RM elbow flexor strength

Ho 2b: 1 RM elbow extensor strength

Ho 2c: 8 RM elbow flexor strength

Ho 2d: 8 RM elbow extensor strength

Ho 3: The 8 week training program will have no significant effect on specific tension of the following muscle groups of the two training groups:

Ho 3a: elbow flexors

Ho 3b: elbow extensors

Ho 4: The 8 week training program will have no significant effect on the following anthropometric variables of the two training groups:

Ho 4a: flexed girth of elbow flexors and extensors

Ho 4b: relaxed girth of elbow flexors and extensors

Ho 4c: sum of biceps and triceps skinfolds

Ho 5: The 8 week training program will have no significant effect on training volume.

Assumptions

1. The training protocols will elicit measurable increases in muscle CSA.

2. The training protocols will elicit measurable increases in strength.

3. The study is of sufficient duration for changes to occur.

4. The subjects will do the prescribed training and will perform the testing with maximal effort.

5. The subjects will be accustomed to lifting loads of a high percentage of their maximum prior to the beginning of the study.

6. Magnetic resonance imaging reflects muscle CSA.

7. Changes in specific tension reflect neural change.

8. Menstrual status will not affect the training response.

Delimitations

1. Only baseline and post-training CSA measurements were taken.

2. Only elbow flexor and extensor muscle groups were studied.

3. The duration of the study was only 8 weeks.

4. Only resistance-trained women participated as subjects.

Limitations

1. Differing weight training experience may have influenced the response to training.

2. Subjects may have had different proportions of fiber types and muscle ultrastructure which may have affected the training response.

3. There may have been individual variability in training response.

4. Other physical activities were not controlled and may have influenced the training response.

5. Diet was not controlled.

6. Hydration was not controlled.

Operational Definitions

1 RM:

The maximum amount of weight which can be lifted for one repetition (Tesch, 1992) using free weights.

8 RM:

The maximum amount of weight which can be lifted consecutively for 8 repetitions using free weights.

10 RM:

The maximum amount of weight which can be lifted consecutively for 10 repetitions.

Cross-Sectional Area:

The area of a muscle group, derived through Magnetic Resonance Imaging, and excluding bone, subcutaneous fat, skin, and neural-vascular structures.

Failure:

When fatigue will not allow another repetition to be completed using the training protocols outlined in the methodology.

Repetition:

A concentric and eccentric muscle action performed in sequence..

Repetition Maximum:

The maximum number of repetitions that can be performed consecutively using the training protocols outlined in the methodology.

Resistance Trained:

In this study the subjects were considered resistance trained if they had been engaged in resistance training of the upper body involving multiple sets of 12 or fewer repetitions per set for a minimum of the previous 2 months. They also had to be able to perform a biceps curl with one third of their body weight.

Set:

The unit consisting of the number of repetitions performed consecutively to failure.

Specific Tension:

The force generated per unit of muscle area (kg/cm2) (Garfinkel & Cafarelli, 1992; Narici, Roi, Landoni, Minetti & Cerretti, 1989). This was determined using the ratio of the 1 RM values to the muscle cross sectional area . Specific tension was determined separately for flexors and extensors. A change in specific tension is considered to be an indicator of neural change.

Strength:

For this study strength was defined as the maximum amount of free weight that could be lifted for 1 or 8 repetitions. 1 RM strength was a measure of concentric strength and was determined through free weights with speed controlled by the individual. 8 RM strength was obtained from the training diaries.

Time under Tension:

The amount of time in seconds that it takes to complete the muscle action.

Training Intensity:

The number of repetitions performed before failure. An 8 RM load refers to a load that induces failure after 8 repetitions (Tesch 1992). Training intensity for both groups was set at 8-10 RM.

Volume:

Training volume was defined as the amount of work performed in a single workout determined by the following formula: repetitions x sets x load x time under tension for the concentric and eccentric muscle actions.

Methodology

Subjects

The subjects were resistance-trained women between 19 and 39 years of age currently doing multiple sets of 12 or fewer repetitions in their exercise regimen for a minimum of 2 months prior to the start of the study and currently able to perform a biceps curl with one third of their body weight. Subjects were randomly assigned to either the super slow group (SS) or the controlled tempo group (CT). Of the initial 26 subjects, 21 subjects completed the 8-wk training study. Two subjects withdrew due to non-related injuries, one subject moved out of the area, one subject exercised her right to withdraw, and the results of one subject were discarded due to non-compliance to the training protocols. Subject characteristics are summarized in Table 1. Using the definitions of Loucks and Horvath (1985), all of the subjects were eumenorrheic with the exception of one subject in the CT group who reported being oligomenorrhic. Only one subject reported oral contraceptive use during the duration of the study. This subject was in the SS group.

The methods and procedures used in this study were approved by the Human Subjects Ethics Committee at the University of Victoria. Written informed consent was obtained from all subjects prior to initial testing (Appendix A). Subjects were asked to maintain their current physical activity level and to refrain from any additional upper body resistance training exercise.

Resistance Training

Training was performed three days a week for eight weeks with a minimum of 48 hours between training sessions. The third training sessions of Week 4 and Week 8 were replaced by 1 RM testing sessions for a total of 22 training sessions. An additional week prior to the start of the training, was used for exercise familiarization and initial testing.

The SS group completed 2 sets of 8-10 RM to failure with an 8 sec:2 sec concentric: eccentric (C:E) ratio. The CT completed 4 sets of 8-10 RM to failure with a 2:2 sec C:E ratio. Both groups had a pause of 1 sec between the concentric-eccentric phases of the lift. Subjects trained in partners and used a metronome to aid with the timing of the muscle actions.

There were two core exercises of biceps curl and triceps extension performed every training session. The core exercises were always performed first with the order alternating between training sessions. An upper body push exercise (bench press or shoulder press) and an upper body pull exercise (lat pulldowns, upright row, seated cable row, or bench pulls) followed the core exercises and were performed in a varied order. A leg flexion exercise, leg extension exercise, and abdominal exercises were also included to provide a balanced program and they were completed after the upper body exercises had been completed. All sets of one exercise were completed before moving on to the next exercise and there was 2- 2.5 min rest between sets.

Exercise technique was standardized using the key technical points of the Coaching Association of Canada (1994) and modified only for biceps curl, which was performed with the subjects standing with the scapulae and buttocks in contact with a wall throughout the lift. All exercises except the abdominal exercises were performed at the prescribed C:E ratio, with timing and exercise technique monitored by the researcher at least once per week. All subjects maintained detailed training diaries in which they recorded for each set, the repetitions, training load, and a rating of perceived exertion (RPE), using a 15 grade scale (Borg, 1982). RPE was used to monitor perceived effort and to aid in motivation. Training volume, in terms of sets x repetitions x training load x time under tension for the concentric and eccentric muscle actions, was equated between the groups at the beginning of the study.

Strength Testing.

1 RM testing of elbow flexors and extensors occurred at week 0 and at the end of weeks 4 and 8. The specific tests were a standing biceps curl (elbow flexors) and supine triceps extension (elbow extensors). These were the same exercises that were used in training. Only the concentric strength of each exercise was tested. Testing followed the methods of Dalton and Wallace (1996). After one unsuccessful attempt, subjects were allowed to make a further attempt with the weight that produced failure, or with a decreased weight. Two consecutive failed attempts ended the test. Testing tempo was controlled by the subject. There was no difference between the groups in time required to

successfully complete a 1 RM attempt. The mean (SD) time of successful 1 RM tests of the SS group was 3.6 (1.8)s and for the CT group it was 3.6 (1.6)s. Exercise order for testing was varied between subjects at the initial testing to randomize any effect of order of testing and the same exercise order maintained for the subsequent tests. Encouragement from other subjects was allowed during testing. 1 RM loads were verified with a calibrated weigh scale after each test.

Muscle Cross-Sectional Area (CSA)

Magnetic resonance imaging (General Electric Signa Horizon 1T) was used to determine the CSA of the upper arm musculature of the right arm of all subjects before and after eight weeks of resistance training. There was a minimum of 48 hours of no resistance training or testing before muscle CSA measurements were obtained. The scans were obtained with the subjects in a prone position with the right arm extended and placed in a knee coil with repetition time and echo time set at 525 and 12 ms, respectively. It was not possible to obtain a clear view of both ends of the humerus so the midpoint of the upper arm was determined anthropometrically following the procedures of the Canadian Society for Exercise Physiology (CSEP) (1996). Multiple coronal scans were used to find this corresponding midpoint on the humerus, measured from the tip of the olecranon. A distance of 70 mm proximal to the midpoint was measured and 12 axonal scans with a slice thickness of 10 mm with 5 mm between slices were obtained along the length of the humerus. These scans were identified sequentially as Rh 1-Rh 12, with Rh 1 the scan at 70 mm proximal to midpoint.

The CSA was calculated using the area program of GE Advantage Windows Core System sdc v12.6.eta. with a screen magnification of 3.5 and the same window width/levels of 2000/500 was used on all images. All areas were measured by the same researcher. Test-retest reliability of CSA scans was determined on 14 randomly selected subjects on 2 different occasions (R=.999). The SEM was 0.7% and was determined using 9 subjects and the method outlined by Baumgartner and Jackson (1991). The outline of each muscle group was traced on each displayed scan and the average of three measurements was used as the CSA measure for the scan. The order of measurement of pre- or post-training was randomized with the researcher blind as to the test occasion and the results. The CSA of the proximal, midpoint, and distal sites was determined as the mean of two consecutive scans with Rh 3-Rh 4, Rh 5- Rh 6, and Rh 7-Rh 8 the locations of the sites, respectively.

Specific Tension

Specific tension (kg/cm^2) for each muscle of the flexor and extensor muscle groups at the proximal, midpoint, and distal sites was determined before and after eight weeks of resistance training. For each site, specific tension of each muscle group was determined by dividing each of the 1 RM test scores for elbow flexors and extensors (kg) by the CSA (cm^2) of the specific musculature.

Anthropometric Measures

Body weight, skinfolds (biceps, triceps, subscapular, suprailliac, and medial calf), and relaxed and flexed arm girths were obtained prior to and following 4 weeks and 8 weeks of resistance training. Body weight was taken in T-shirt and shorts or tights. Skinfold measurements followed the procedures of CSEP (1996). The five skinfold values were summed to give a sum of skinfolds (SOS) value. Girths of the right arm were measured at the midpoint to the nearest 0.1 cm using a metal anthropometric tape with the subject standing. The relaxed girth was measured with the arm relaxed at the side. Flexed girths were taken at the midpoint of the arm with the humerus parallel to the floor and the elbow flexed at 90 degrees. All anthropometric measurements were taken at least 48 hrs after a resistance training or testing session by the same experienced testers.

8 RM Strength

8 RM strength, was obtained from the training diaries. The highest weight that a subject was able to perform 8 repetitions during Week 1, 4, and 8, using the outlined technique, was used as the 8 RM strength value. Thus this value also represented maximum training load.

Volume

The volume of each subject's training session was calculated by repetitions x sets x load x time under tension for the C and E muscle actions. The mean weekly volume of each group was determined from the volume of the individual training sessions of the subjects in each group.

Statistical Analysis

There were no significant differences in initial 1 RM strength of elbow flexors and extensors, 8 RM elbow flexor strength, or the anthropometric measures, so these variables were analyzed by separate 2 by 3 repeated measures analysis of variance (ANOVA). Analysis of covariance was used to analyze 8 RM elbow extensor strength due to differences in initial 8 RM extensor strength. No significant differences in the pre-training measures of CSA and specific tension were found, so separate 2 by 2 repeated measures ANOVA were used for analysis. When significant differences were found in the ANOVA analyses, independent t-tests and t-tests for paired samples were used to determine differences between and within groups. Profile analysis was used to examine the response to training. Statistical significance for all analyses was set at $p<.05$.

Results

Subjects

Subject characteristics are shown in Table 1. There were no initial statistically significant differences between the SS and CT groups in terms of age, weight, training years, and SOS, and no significant differences were observed over the period of the study. The SS group was significantly taller than the CT group. Weight and SOS did not change significantly between test occasions. Training compliance (percent of sessions completed) of those subjects included in the analyses was 94.8 percent for the SS group and 93.2 percent for the CT group. No subject missed two or more consecutive sessions.

1 RM Strength

The SS and CT groups experienced significant increases in elbow flexor ($F_{1,19} = 89.96$, $p<.01$) and extensor ($F_{1,19} = 120.42$, $p<.01$) 1 RM strength between pre- and post-training. Elbow flexors and extensors exhibited the same response in 1 RM strength with no group main effect and significant main effects for the three test occasions (flexors $F_{2,38} = 68.92$, $p<.01$; extensors $F_{2,38} = 84.48$ $p<.01$). Data for the test occasions are shown in Table 2.

Data for percent change in strength in 1 RM strength are shown in Table 3. Significant increases in 1 RM strength for both muscle groups occurred from Week 0-4, and Week

4-8 (flexors $F_{1,19}$ = 23.62, p<.01; extensors $F_{1,19}$ = 21.50 p<.01) with no differences between the groups. Increases in the CT group from Week 4-8 were not significant.

Muscle CSA

Data for flexors and extensor CSA are displayed in Tables 4 and 5, respectively. There were significant main effects for time at all sites but there was no group effect for any of the sites. Significant increases occurred in flexor CSA of both groups between Weeks 0-8 at the proximal, midpoint, and distal sites, $F_{1,19}$ = 8.75, p<.01; $F_{1,19}$ = 10.88, p<.01; $F_{1,19}$ = 18.22, p<.01, respectively. Significant increases occurred in extensor CSA of both groups between Weeks 0-8 at the proximal, midpoint, and distal sites, $F_{1,19}$ = 41.73, p<.01; $F_{1,19}$ = 49.88, p<.01; $F_{1,19}$ = 41.73, p<.01, respectively. There were no significant differences between groups in flexor CSA at any site, although CT group did not increase significantly at any site. Both groups had significant increases in extensor CSA at all sites with no differences occurring between the groups.

Table 6 shows the CSA values for the mean of the sites. There were no group main effects or group and time interaction effects but there were time main effects. Significant increases occurred for flexor ($F_{1,19}$ = 17.60, p<.01) and extensor ($F_{1,19}$ = 72.51, p<.01) CSA with no differences occurring between the groups.

Specific Tension

Specific tension data for the proximal, midpoint, and distal locations of the flexors and extensors are presented in Tables 7 and 8, respectively. Significant main effects occurred only for time at all sites. There was a significant increase in specific tension of the flexors at the proximal, midpoint, and distal sites; $F_{1,19} = 6.56$, $p<.05$; $F_{1,19} = 11.74$, $p<.01$; $F_{1,19} = 41.73$, $p<.01$, respectively. Significant increases in specific tension of the SS group occurred only at the midpoint and distal sites and significant increases occurred at the proximal and distal sites of the CT group. Significant increases in specific tension of the extensors occurred in both groups at the proximal, midpoint, and distal locations; $F_{1,19} = 77.12$, $p<.01$; $F_{1,19} = 85.19$, $p<.01$; $F_{1,19} = 77.96$, $p<.01$; respectively. There was no difference between the groups at any site.

Table 6 shows the specific tension values for the mean of the sites. There were no significant group main effects or group and time interaction effects but there were time main effects. Significant increases occurred for flexor ($F_{1,19} = 12.19$, $p<.01$) and extensor ($F_{1,19} = 83.71$, $p<.01$) specific tension with no differences occurring between the groups.

Anthropometrics

Data for relaxed arm girth, flexed arm girth, and sum of biceps and triceps skinfolds are presented in Table 9. Relaxed arm girth had no significant group or group and time effects and exhibited significant increases between test occasions ($F_{2,38} = 44.19$, $p<.01$). Similarily flexed girth also had no significant group or group and time effects and significant increases occurred between test occasions ($F_{2,38}$ = 23.18, p<.01). Biceps and triceps skinfolds did not change significantly during the study for either group. The SS group had significant increases between all test occasions for both relaxed and flexed girth while the CT group had significant increases only between Weeks 0-4.

8 RM Strength

Table 10 displays the data for 8 RM strength. Significant increases in 8 RM strength occurred from Week 1-8 for the flexors ($F_{1,19}$= 69.61, p<.01) and extensors ($F_{1,18}$= 163.85 p<.01) with no differences between groups. There was no group main effect and no group by time interaction occurred. Elbow flexion 8 RM strength did not differ initially between the groups (p = 0.07) and there was no group main effects but significant increases occurred over the three test occasions ($F_{2,38}$ = 52.78, p<.01). Elbow extensor 8 RM strength differed initially between the groups and there was a significant group by time interaction ($F_{1,18}$= 8.29, p=.01), and significant strength increases between the three test occasions ($F_{1,19}$= 55.26, p<.01). A significant interaction effect occurred between Weeks 4-8 ($F_{1,19}$= 13.1, p<.01). 8 RM flexor and extensor strength for the SS group was less than the CT group initially but was greater than the CT group by week 8. The SS group increased significantly in training weights of the flexors and extensors at Weeks 4 and 8. The CT group had no significant increases in 8 RM strength after the first 4 weeks.

Training Volume

Weekly average training volume per session for each of the eight training weeks is shown in Table 11, Figure 1, and Figure 2. The elbow extension exercise exhibited only significant main effects for time ($F_{17,133} = 66.88$, $p<.05$). Training volume of the SS group for the elbow extension exercise differed significantly from that of the CT group in weeks 5 and 7. Significant group main effects were found for the elbow flexor exercise (($F_{1,19} = 5.41$, $p<.05$) and for time ($F_{17,133} = 23.03$, $p<.05$). There was a significant interaction effect for the elbow flexor exercise between weeks four and five ($F_{1,19} = 7.27$, $p<.05$). Training volume of the SS group for the elbow flexion exercise was significantly greater than that of the CT group during Weeks 4 to 8. For both the elbow flexion and extension exercises, the groups did not initially differ in training volume nor for the first four weeks of training.

Table 1

Subject characteristics (means and SD)

Variable	Super Slow n=13	Controlled Tempo n=8
Age	28.6 (5.5)	26.3 (8.2)
Weight (kg)	72.4 (14.5)	62.8 (9.3)
Height (cm)	171.1 (7.7)*	162.9 (3.9)*
Training (yr)	5.4 (2.6)	4.4 (1.9)
SOS (mm)	70.5 (22.8)	64.9 (10.9)

* indicates significant differences between groups $p < .05$

Table 2

Mean (SD) 1 RM strength (kg) of the elbow flexors and extensors of the Super Slow and Controlled Tempo groups at Week 0, 4, and 8

Group	1 RM Flexors	1 RM Extensors
Super Slow (n=13)		
Week 0	24.2 (4.6)	19.7 (3.6)
Week 4	27.7 (4.1)**	26.0 (4.4)**
Week 8	29.6 (3.6)**	32.6 (6.2)**
Controlled Tempo (n=8)		
Week 0	23.4 (3.5)	20.4 (6.0)
Week 4	26.8 (4.0)**	26.5 (7.6)**
Week 8	28.4 (4.6)**	31.6 (9.5)**

** represents statistical significance ($p < .01$) from the previous test occasion

Table 3

Mean (SD) percent increases in 1 RM strength of the elbow flexors and extensors of the Super Slow and Controlled Tempo groups at Week 0-4, and Week 4-8

Group	Flexors	Extensors
Super Slow (n=13)		
Week 0-4	24.2 (3.1)**	33.5 (5.2)**
Week 4-8	7.5 (1.5)*	26.1 (5.4)
Controlled Tempo (n=8)		
Week 0-4	15.1 (3.9)**	31.8 (6.8)**
Week 4-8	5.9 (1.7)	19.5 (5.2)

* represents statistical significance ($p < .05$) from the previous test occasion

** represents statistical significance ($p < .01$) from the previous test occasion

Table 4

Mean (SD) elbow flexor CSA (cm^2) of the Super Slow and Controlled Tempo groups at the proximal, midpoint, and distal sites at Week 0 and 8

Group	Proximal CSA	Midpoint CSA	Distal CSA
Super Slow (n=13)			
Week 0	6.0 (0.9)	8.3 (1.5)	12.7 (2.1)
Week 8	6.6 (0.8)*	9.2 (1.3)**	13.4(2.0)**
Controlled Tempo (n=8)			
Week 0	6.8 (1.3)	8.4 (1.2)	11.6 (1.4)
Week 8	7.3 (1.8)	8.9 (1.4)	12.1 (1.8)

* represents statistical significance ($p < .05$) from the previous test occasion

** represents statistical significance ($p < .01$) from the previous test occasion

Table 5

Mean (SD) elbow extensor CSA (cm^2)of the Super Slow and Controlled Tempo groups at the proximal, midpoint, and distal sites at Week 4 and 8

Group	Proximal CSA	Midpoint CSA	Distal CSA
Super Slow			
Week 0	17.1 (2.9)	16.9 (3.0)	15.2 (3.1)
Week 8	19.7 (3.4)**	19.5 (3.3)**	17.2 (3.5)**
Controlled Tempo			
Week 0	17.7 (2.7)	17.4 (3.1)	15.2 (3.4)
Week 8	19.1(2.5)*	19.2 (3.0)**	16.6 (3.3)*

* represents statistical significance ($p < .05$) from the previous test occasion

** represents statistical significance ($p < .01$) from the previous test occasion

Table 6

Mean (SD) value for elbow flexor and extensor CSA (cm^2) and value for specific tension (kg/cm^2)of the Super Slow and Controlled Tempo groups for Week 0 and 8

	CSA		Specific Tension	
Group	Flexor	Extensor	Flexor	Extensor
Super Slow (n=13)				
Week 0	9.0 (1.4)	16.4 (2.8)	3.0 (0.6)	1.2 (0.2)
Post	9.5 (1.3)**	18.8 (3.2)**	3.3 (0.5)*	1.8 (0.3)**
Controlled Tempo (n=8)				
Week 0	8.9 (1.2)	16.8 (3.0)	2.8 (0.4)	1.2 (0.2)
Post	9.3 (1.4)	18.3 (2.9)*	3.1 (0.3)*	1.7 (0.2)**

* represents statistical significance ($p < .05$) from the previous test occasion

** represents statistical significance ($p < .01$) from the previous test occasion

Table 7

Mean (SD) elbow flexor specific tension (kg/cm^2) at the proximal, midpoint, and distal sites of the Super Slow and Controlled Tempo groups at Week 0 and 8

Group	Proximal	Midpoint	Distal
Super Slow (n=13)			
Week 0	4.1 (0.9)	3.0 (0.6)	2.0 (0.4)
Week 8	4.5 (0.7)$_a$	3.3 (0.5)*	2.2 (0.3)**
Controlled Tempo (n=8)			
Week 0	3.5 (0.7)	2.8 (0.4)	2.0 (0.2)
Week 8	3.9 (0.6)*$_a$	3.2 (0.4)	2.3 (0.2)*

$_a$ indicates significant differences ($p < .05$) between the groups.

* represents statistical significance ($p < .05$) from the previous test occasion

** represents statistical significance ($p < .01$) from the previous test occasion

Table 8

Mean (SD) elbow extensor specific tension (kg/cm^2) at the proximal, midpoint, and distal sites of the Super Slow and Controlled Tempo groups at Week 0 and 8

Group	Proximal	Midpoint	Distal
Super Slow (n=13)			
Week 0	1.2 (0.2)	1.2 (0.2)	1.3 (0.2)
Week 8	1.7 (0.3)**	1.7 (0.2)**	1.9 (0.31)**
Controlled Tempo (n=8)			
Week 0	1.1 (0.2)	1.2 (0.2)	1.3 (0.2)
Week 8	1.6 (0.3)**	1.6 (0.2)**	1.9 (0.2)**

* represents statistical significance ($p < .05$) from the previous test occasion

** represents statistical significance ($p < .01$) from the previous test occasion

Table 9

Mean (SD) relaxed and flexed girth (cm) and sum of triceps and biceps skinfolds (mm) of the Super Slow and Controlled Tempo groups at Week 0, 4, and 8

Group	Relaxed Girth	Flexed Girth	Sum of biceps and triceps skinfolds
Super Slow (n=13)			
Week 0	29.6 (2.9)	30.8 (2.6)	27.4 (9.2)
Week 4	30.7 (2.4)**	32.0 (2.4)**	27.0 (7.6)
Week 8	31.1 (0.6)*	32.2 (2.5)*	26.1 (6.8)
Controlled Tempo (n=8)			
Week 0	29.0 (2.7)	29.7 (2.1)	25.1 (4.7)
Week 4	29.7 (2.4)*	30.8 (2.3)**	24.8 (4.7)
Week 8	30.0 (2.3)	30.8 (2.3)	24.8 (4.6)

* represents statistical significance ($p < .05$) from the previous test occasion

** represents statistical significance ($p < .01$) from the previous test occasion

Table 10

Mean (SD) 8 RM strength (kg) of the elbow flexors and extensors of the Super Slow and Controlled Tempo groups at Week 0, 4, and 8

Group	8 RM Flexors	8 RM Extensors
Super Slow (n=13)		
Week 0	13.9 (3.8)	10.8 (2.3)$_a$
Week 4	18.6 (2.7)**	16.4 (3.6)**
Week 8	20.8 (2.5)**	20.3 (3.7)**
Controlled Tempo (n=8)		
Week 0	17.0 (3.4)	14.5 (4.3)$_a$
Week 4	20.0 (4.6)**	18.1 (4.5)**
Week 8	20.4 (4.4)	19.5 (5.1)

$_a$ indicates significant differences ($p < .05$) between the groups.

* represents statistical significance ($p < .05$) from the previous test occasion

** represents statistical significance ($p < .01$) from the previous test occasion

Table 11

Mean (SD) weekly mean training session volume (repetitions x sets x load x time under tension) of the Super Slow and Controlled Tempo groups for the eight training weeks

	Super Slow n=13		Controlled Tempo n=8	
Week	Biceps Curl	Elbow Extension	Biceps Curl	Elbow Extension
1	2479 (540)	2021 (405)	2297 (627)	2095 (695)
2	2785 (298)	2628 (544)	2560 (555)	2364 (751)
3	2987 (439)	2774 (524)	2601 (687)	2572 (624)
4	3156 (450)	2998 (571)	2804 (795)	2739 (789)
5	3445 (478)**$_a$	3334 (458)*	2731 (624)**$_a$	2789 (672)*
6	3557 (480)*	3377 (597)	2822 (713)*	2885 (674)
7	3601 (648)*	3334 (458)*	2849 (660)*	2789 (672)*
8	3636 (557)**	3377 (597)	2748 (631)**	2885 (673)

Note. $_a$ indicates significant interaction occurred from the previous week ($p \leq .05$)

* represents statistical significance ($p < .05$) between groups

** represents statistical significance ($p < .01$) between groups

Figure 1. Weekly mean (SE) training session volume (repetitions x sets x load x time under tension) of the elbow flexor exercise of the Super Slow (n=13) and Controlled Tempo (n=8) groups for the eight training weeks. † indicates significant interaction occurred from the previous week ($p \leq .05$). * represents statistical significance ($p < .05$) between groups. ** represents statistical significance ($p < .01$) between groups.

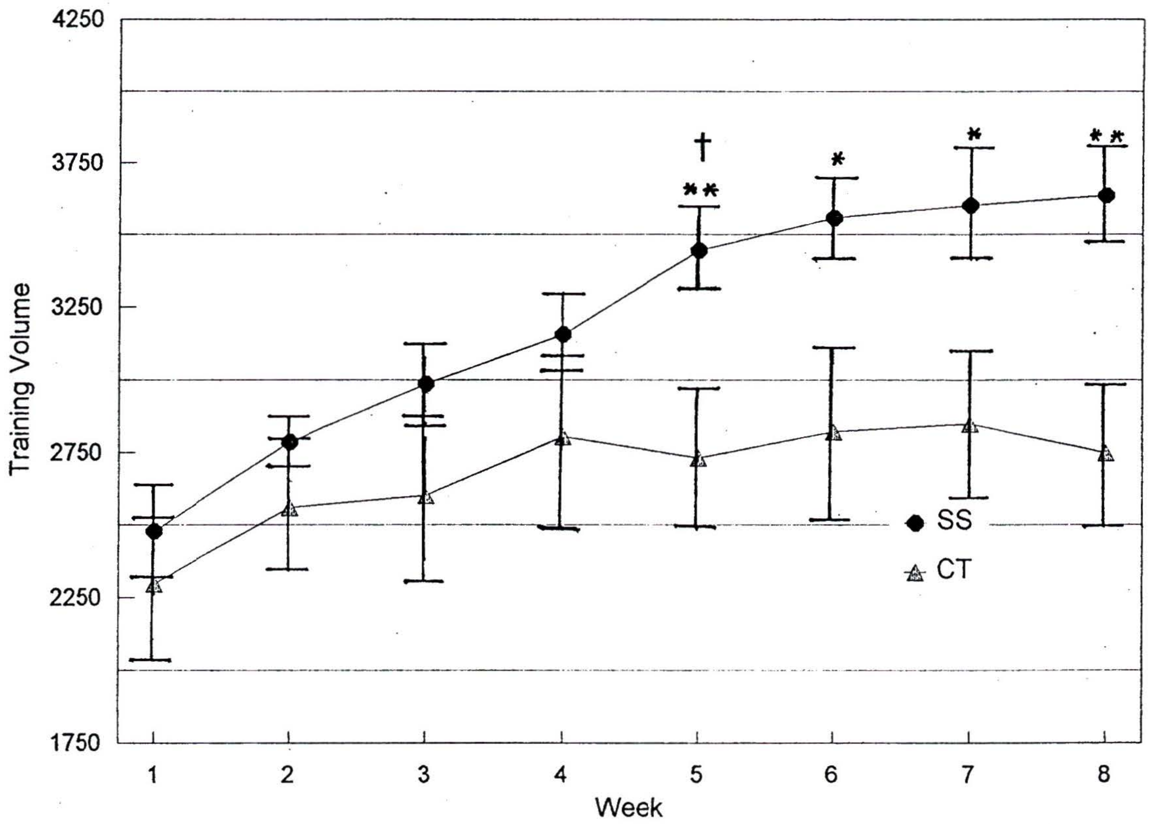
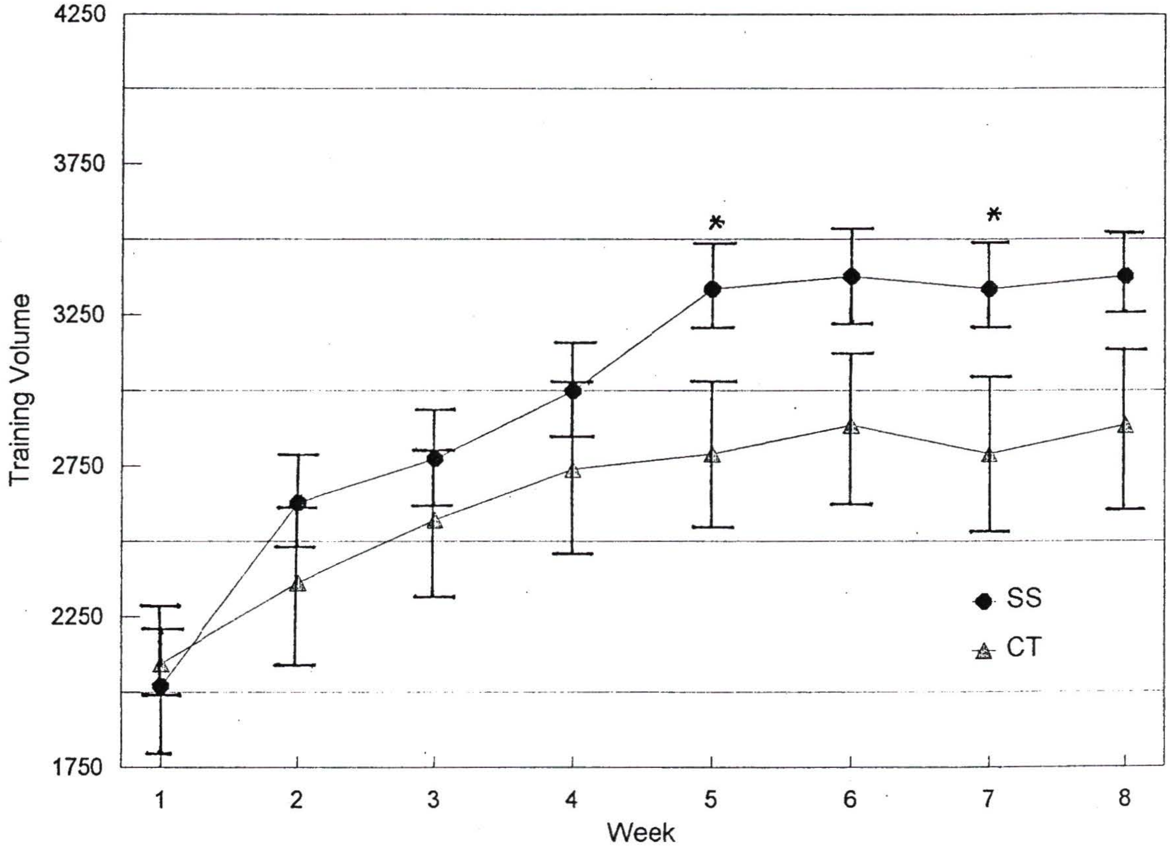

4250
3750
3250
2750
2250
1750
Training Volume
†
**
*
*
**
SS
CT
1
2
3
4
5
6
7
8
Week

Figure 2. Weekly mean (SE) training session volume (repetitions x sets x load x time under tension) of the elbow extensor exercise of the Super Slow (n=13) and Controlled Tempo (n=8) groups for the eight training weeks. * represents statistical significance ($p < .05$) between groups. ** represents statistical significance ($p < .01$) between groups.



Training Volume
4250
3750
3250
2750
2250
1750
1
2
3
4
5
6
7
8
Week
*
*
SS
CT

Discussion

1 RM Strength

The training programs were equally effective in increasing 1 RM strength of elbow flexors, with the SS group improving 22.3 percent and the CT group improving 21.4 percent. Elbow extensor maximal strength increased 65.5 percent in the SS group and 54.9 percent in the CT group. These results of significant increases in groups were consistent with other studies that have manipulated time under tension as an independent variable (Harmon, Morrissey, Frykman, & Han, 1995; Palmieri, 1987; Young & Bilby, 1993).

Studies using resistance-trained women are few, especially those examining upper body strength changes. Bell, Syrotuik, Socha, MacLean, and Quinney (1997), using resistance- trained women, employed repetitions, sets, and exercises similar to this study, reported increases of 20.8 percent in bench press after 8 weeks. This is comparable to the improvements in elbow flexion in this study but not in elbow extension, which bench press involves. Although the increases in elbow extension strength were large, similar increases in upper and lower body strength in untrained women over 14-20 weeks of training have been found (Calder, Chilibeck, Webber, & Sale, 1994; Cureton, Collins, Hill, & Mcelhannon, 1988; Starkey et al., 1996; Staron et al., 1991). It is possible that the elbow extensors had more potential for strength gains because they are not stressed as much as the flexors in daily activities, or the relative training status of the extensors may have differed from that of the flexors due to less emphasis on extensor exercises in the subjects' previous training programs.

Muscle CSA

Muscle hypertrophy occurred in both groups. This was reflected by increases in CSA and arm girths. The accuracy of anthropometric measures of girths and girths corrected for skinfolds to detect changes in muscle CSA is generally questioned (Katch & Hortobagy, 1990; Maughan, 1984) due to low reliability between muscle imaging techniques and anthropometric measures (Doxey, 1988; Housh et al., 1995; Weiss, 1987; Young, Stokes, Round, & Edwards, 1983). The present study did not determine the relationship between MRI determined muscle CSA and the anthropometric measurements in terms of reliability or a regression equation. However, the significant pre- to post-training increases of both the relaxed and flexed girths, without corresponding changes in skinfolds, reflected the significant changes in muscle CSA determined by MRI. This suggests that the girth measurements were sensitive to change in muscle area, although they underestimated the percentage change. Cureton et al. (1988) also found that arm girths and anthropometric estimations of muscle CSA detected similar changes in CSA determined through computed tomography. Similarily, Young and Bilby (1993) and Young and coworkers (1983) reported increases in mid-thigh circumference as well as hypertrophy determined by ultrasound. In these studies changes in girth underestimated hypertrophy determined through muscle imaging techniques, as was found in this study. The implication of greater girth changes from pre- to mid- training than from mid- to post-training in this study is that greater hypertrophy occurred during the first four weeks of training. Significant improvements in maximum strength and hypertrophy have been found in studies of 7.5 weeks or less in untrained (Jackson, Dickinson, & Ringel, 1990; Tesch & Karlsson, 1985) and trained (Staron, et al. 1991; Tesch & Karlsson) subjects.

Hypertrophy was different for the two muscle groups. While both groups had significant increases in extensor CSA, only the SS group had significant increases in flexor CSA. This suggests that the SS training protocol was more effective in stimulating hypertrophy in the flexors. The significant hypertrophy of the extensors for both groups may be due to the larger proportion of Type II fibers in the extensors than the flexors (Endstrom & Nystrom, 1969; Johnson, Polgar, Weightman, & Appleton, 1973).

The amount of hypertrophy in different fibre types was not examined in this study. A consistent observation by others is greater relative hypertrophy occurring in Type II than Type I fibers as a response to resistance training (Dons, Bollerup, Bonde-Petersen, & Hancke, 1979; Jackson, Dickinson, & Ringel, 1990; Jones & Rutherford, 1986; MacDougall, Elder, Sale, Moroz, & Sutton, 1980; Staron et al., 1991; Staron et al., 1994; Hakkinen & Komi, 1985). Due to their larger size, Type II fibers can produce more force than Type I fibers (Wilmore & Costill, 1994) and thus hypertrophy of Type

II fibers could explain the greater of hypertrophy of the extensors as compared to the flexors. The greater hypertrophy of the extensors may also be related to hypertrophy of Type II fibers. The extensors are often not stressed during functional daily activity (MacDougall et al., 1980) and could have had more potential for hypertrophy.

Specific Tension

Increases in specific tension indicated that neural changes to the training protocols occurred in both groups. This is in agreement with other studies using similar repetitions (Cureton et al., 1988; Chestnut; 1995; Garfinkel & Cafarelli, 1992; Narici et al. 1989). The neural changes can be partially related to coordination and learning (Rutherford & Jones, 1986), as the training protocols required a different execution of the muscle actions as well as strict adherence to technique. Specific tension could also have increased due to increased connective tissue attachments, as suggested by Rutherford, Jones and Parker (1989). New attachments between the tendons and intermediate points on the fibre could increase the force per unit CSA (Rutherford, Jones, & Parker) by increasing transmission of force between the sarcomeres and the skeletal system (Enoka, 1988).

Increases in specific tension of the extensors could have resulted from the unfamiliarity of the subjects with the extension exercises. However, differences may also be attributable to fibre type proportions of the flexors and extensors with the extensors having a higher proportion of Type II fibers than the flexors (Endstrom & Nystrom, 1969; Johnson, Polgar, Weightman, & Appleton, 1973). The higher threshold motor units have a greater force generating capability due to their larger size (Wilmore & Costill, 1994). If increased ability to recruit Type II motor units was a change induced by the training protocols, this could account for the increases in 1 RM strength and the resultant effect on specific tension.

The arrangement of muscle fibers within a muscle also influences force production. The elbow extensors are a pennate muscle and an increase of the angle of pennation of fibre insertion into the tendons could allow a greater force generating capability of the muscle (Jones, Rutherford, & Parker, 1989) and increase the ability of the muscle to exert more force per unit of CSA. This was not examined in the present study but if this had occurred, it could explain the large increase in 1 RM of the elbow extensors and the resultant effects on specific tension.

8 RM Strength and Training Volume

The overall trend of greater increases in 1 RM, hypertrophy, and specific tension of the SS group was also reflected in 8 RM strength (defined as the maximum load used during training for 8 repetitions). Increases in 8 RM of the flexors was 50 percent for the SS group and 20 percent for the CT group. Extensor 8 RM strength increased 88 and 35 percent for the SS and CT group, respectively. The SS group's initial 8 RM was less than that of the CT group. The effects of the longer time under tension included changes that led to the SS group having a greater 8 RM than the CT group by the eighth week of the study. This suggests that increased time under tension may have been the stimulus for the trend towards the greater neuromuscular changes seen in the SS group.

The training response, in terms of volume, differed between the groups and between muscle groups in terms of volume. Training volume is considered to be important in order the quantify the total work completed by training groups so that differences between groups can be attributed to differing training protocols and not the amount of work performed. Volume has been defined as; repetitions x sets (Baker, Wilson, & Carlyon, 1994; Kraemer, 1983; Stone, O'Bryant, & Garhammer, 1981; Ostrowski, 1994), as repetitions x sets x load (Calder et al., 1994; Starkey et al, 1996; Tesch, 1992), and as repetitions x sets x percent 1 RM (Ben-Sira, Ayalon, & Tavi, 1995; Cureton et al, 1988; O'Hagan, Sale, MacDougall, & Garner, 1995; Schmidtbleicher & Haralambie, 1981; Willoughby, 1991). Any of the above definitions of volume would give the CT group a volume of approximately twice that of the SS group throughout the training period. With the inclusion of time under tension, training volume was initially equal between the groups. The significantly greater increases in volume, as well as 8 RM strength, in the SS group during the last four weeks of training may have been the stimulus for the trend toward larger increases of the other variables in this group. Training volume is often considered to be important for continued long term development of strength and hypertrophy with higher volume necessary for continued improvements (Kraemer et al., 1995). The results of this study indicate that time under tension may be an important variable that should be included in consideration of volume.

Conclusions

In conclusion, although the response of the SS and CT groups in terms of 1 RM flexor and extensor strength, extensor hypertrophy, and flexor and extensor specific tension did not differ, the trend was for greater increases in all of the variables with the SS group. MRI measured hypertrophy of the flexors in the CT group was non-significant. It is possible that if the training period had been extended, significant differences between the two groups in the other variables might have occurred. The results of this study suggest that the slow execution of resistance exercise performed to technical failure is effective at producing neuromuscular changes in resistance trained women. The differing changes between the groups appeared to be due to a differential response to the training stimuli, with the SS group able to utilize a greater training weight and complete a larger training volume, with volume defined to include time under tension. Two sets performed with a very slow concentric phase, were as effective as four sets, performed at a quicker tempo, in producing neuromuscular changes. Whether a similar response would be found in populations other than resistance trained women is not known.

REFERENCES

Anderson, T., & Kearney, J. T. (1982). Effects of three resistance training programs on muscular strength and absolute and relative endurance. Research Quarterly for Exercise and Sport, 53(1), 1-7.

Atha, J. (1981). Strengthening muscle. Exercise and Sport Science Reviews, 9. 1-73.

Barnett, J. G., Holly, R. G., & Ashmore, C. R. (1980). Stretch-induced growth in chicken wing muscles: biochemical and morphological characterization. American Journal of Physiology, 239, C39-C46.

Baker, D., Wilson, G., & Carlyon, R. (1994). Periodization: The effect on strength of manipulating volume and intensity. Journal of Strength and Conditioning Research, 8(4), 235-242.

Bell, G., Syrotuik, D., Socha, T., Maclean, I., & Quinney, H. A. (1997). Effect of strength training and concurrent strength and endurance training on strength, testosterone, and cortisol. Journal of Strength and Conditiioning Research, 11(1), 57-64.

Ben-Sira, D., Ayalon, A., & Tavi, M. (1995). The effect of different types of strength training on concentric strength in women. Journal of Strength and Conditioning Research, 9(3), 143-148.

Borg, G. A. V. (1982). Psychological bases of perceived exertion. Medicine and Science in Sports and Exercise, 14(5), 377-381.

Buresova, M, Gutmann, E., & Klicpera, M. (1969). Effect of tension upon rate of incorporation of amino acids into proteins of cross-striated muscle. Experientia, 25, 144-145.

Caiozzo, V. J., Perrine, J. J., & Edgerton, V. R. (1981). Training-induced alterations of the in vivo force-velocity relationship of human muscle. Journal of Applied Physiology: Respirational, Environmental and Exercise Physiology, 51(3), 750-754.

Calder, A. W., Chilibeck, P. D., Webber, C. E., & Sale, D. G. (1994). Comparison of whole and spilt weight training routines in young women. Canadian Journal of Applied Physiology, 19(2), 185-199.

Canadian Society for Exercise Physiology (1996). Canadian Physical Activity, Fitness, and Lifestyle Appraisal: Guide to Healthy Active Living. Ottawa, Ontario, Canada: Canadian Society for Exercise Physiology.

Coaching Association of Canada (1994). Strength training with weights [Video-tape].

Chestnut, J. L. (1995). The effects of 4RM and 10RM weight training protocols on strength, cross-sectional area, and specific tension in untrained males. Unpublished master's thesis, University of Victoria, Victoria, British Columbia, Canada.

Cureton, K. J., Collins, M. A., Hill, D. W., & Mcelhannon, Jr., F. M. (1988). Muscle Hypertrophy in men and women. Medicine and Science in Sports and Exercise, 20(4), 338-334.

Dalton, N. J., & Wallace, J. D. (1996). Strength testing protocols for college-age women. National Strength and Conditioning Association Journal, 18(2), 7-10.

Dons, B., Bollerup, K., Bonde-Petersen, F., & Hancke, S. (1979). The effect of weight-lifting exercise related to muscle fiber cross-sectional area in humans. European Journal of Applied Physiology and Occupational Physiology, 40, 95-106.

Doxey, G. E. (1988). Assessing thigh fat and muscularity with anthropometric and real time ultrasonography techniques. Journal of Applied Sport Science Research, 1(2), 20-24.

Enoka, R. M. (1988). Muscle strength and its development. New perspectives. Sports Medicine, 6, 146-168.

Ewing, J. L., WolfeD. R., Rogers, M. A., Amundson, M. L., & Stull, G. A. (1990). Effects of velocity of isokinetic training on strength, power, and quadriceps muscle fibre characteristics. European Journal of Applied Physiology and Occupational Physiology, 61, 159-162.

Fuglevand, A. J., Zackowski, K. M., Huey, K. A., & Enoka, R. M. (1993). Impairment of neuromuscular propagation during human fatiguing contractions at submaximal forces. Journal of Physiology, 460, 549-572.

Garfinkel, S., & Cafarelli, E. (1992). Relative changes in maximal force, EMG, and muscle cross-sectional area after isometric training. Medicine and Science in Sports and Exercise, 24(11), 1220-1227.

Garland, S. J., Enoka, R. M., Serrano, L. P., & Robinson, G. A. (1994). Behavior of motor units in human biceps brachii during a submaximal fatiguing contraction. Journal of Applied Physiology, 76(6), 2411-2419.

Goldberg, A.L., Etinger, J. D., Goldspink, D. F., & Jablecki, C. (1975). Mechanism of work-induced hypertrophy of skeletal muscle. Medicine and Science in Sports and Exercise, 7(4), 248-261.

Harman, E., Morrissey, M, Frykman, P, & Han, K. (1994). Differential training effects of barbell squat exercise performed at normal and fast speeds [Abstract]. National Strength and Conditioning Association Journal, 18(2), 196.

Hay, J G., Andrews, J. G., & Vaughan, C. T. (1980). Some biomechanical aspects of strength training. In W. Baumann (Ed.), International Symposium of Biomechanics of Sport. Schorndorf, Germany: Verlag Karl Hofmann.

Housh, D. J., Housh, T. J., Weir, J. P., Weir, L. L., Johnson, G. O., & Stout, J. R. (1995). Anthropometric estimation of thigh muscle cross-sectional area. Medicine and Science in Sports and Exercise, 27(5), 784-791.

Ikai, M., & Fukunaga, T.(1968). Calculation of muscle-strength per unit cross-sectional area of human muscle by means of ultrasonic measurement. International Zeitschrift fur angewandte Physiologie einschliesslich Arbeitsphysiologie, 26, 26-32.

Ikai, M., & Fukunaga, T.(1970). A study on training effect on strength per unit cross-sectional area of muscle by means of ultrasonic measurement. International Zeitschrift fur angewandte Physiologie einschliesslich Arbeitsphysiologie, 28, 173-180.

Jackson, C. G. R., Dickinson, A. L., & Ringel, S. P. (1990). Skeletal muscle fiber area alterations in two opposing modes of resistance-exercise training in the same individual. European Journal of Applied Physiology, 61, 37-41.

Jones, D. A., Rutherford, O. M., & Parker, D. F. (1989). Physiological changes in skeletal muscle as a result of strength training. Quarterly Journal of Experimental Physiology, 72(233-256).

Katch, F. I., & Hortobagyi, T. (1990). Validity of surface anthropometry to estimate upper-arm muscularity, including changes with body mass loss. American Journal of Clinical Nutrition, 52, 591-595.

Kraemer, W. J. (1983). Exercise prescription in weight training: manipulating program variables. National Strength and Conditioning Association Journal, June-July, 58-59.

Kraemer, W. J., Newton, R. U., Bush, J., Volek, J., Triplett, N. T., & Koziris, L. P. (1995). Varied multiple set resistance training program produces greater gains than single set program [Abstract]. Medicine and Science in Sports and Exercise, 27(5), S195.

MacDougall, J. D. (1986). Adaptability of muscle to strength training-a cellular approach. In B. Saltin (Ed.), Biochemistry of Exercise VI (pp. 501-513). Champaign, IL: Human Kinetics.

MacDougall, J. D., Elder, G. C. B., Sale, D. G., Moroz, J. R., & Sutton, J. R. (1980). Effects of strength training and immobilization on human muscle fibres. European Journal of Applied Physiology and Occupational Physiology, 43, 25-34.

Maton, B. (1981). Human motor unit activity during the onset of muscle fatigue in submaximal isometric contraction. European Journal of Applied Physiology and Occupational Physiology, 46, 271-281.

Maughan, R. J. (1984). Relationship between muscle strength and muscle cross-sectional area. Implications for training. Sports Medicine, 1, 263-269.

Maughan, R. J., Watson, J. S., & Weir, J, (1983). Strength and cross-sectional area of human skeletal muscle. Journal of Physiology, 338, 37-49.

McDonagh, M. J. N, & Davies, C. T. M. (1984). Adaptive response of mammalian skeletal muscle to exercise with high loads. European Journal of Applied Physiology and Occupational Physiology, 52, 139-155.

Mikesky, A. E., Matthews, W., Giddings, C. J., & Gonyea, W. J. (1989). Muscle enlargement and exercise performance in the cat. Journal of Applied Sport Science Research, 3(4), 85-92.

Moffroid, M. T., & Whipple, R. H. (1970). Specificity of speed of exercise. Physical Therapy, 50, 1692-1700.

Moritani, T. (1992). Time course for adaptations during strength and power training. In P. V. Komi (Ed.), Strength and power in sports (pp. 266-278). London: Blackwell Scientific Publications.

Moritani, T., & deVries, H. A. (1979). Neural actors versus hypertrophy in the time course of muscle strength gain. American Journal of Physical Medicine, 58(3), 115-130.

Narici, M. V., Roi, G. S., Landoni, L., Minetti, A. E., & Cerretelli, P. (1989). Changes in force, cross-sectional area and neural activation during strength training and detraining of the human quadriceps. European Journal of Applied Physiology and Occupational Physiology, 59, 310-319.

O'Hagan, F. T., Sale, D. G., Macdougall, J. D., & Garner, S. H. (1995). Comparative effectiveness of accommodating and weight resistance training modes. Medicine and Science in Sports and Exercise, 27(8), 1210-1219.

Ostrowski, K. (1994). Muscle hypertrophy - a question of volume. Strength and Conditioning Coach, 2(3), 25-27.

Palmieri, G. A., (1987). Weight training and repetition speed. Journal of Applied Sport Science Research, 1, 36-38.

Poliquin, C. (1990). Theory and methodology of strength training. In: NCCP Task 2 Readings, Ottawa, Canada: Coaching Association of Canada.

Rutherford, O. M., & Jones, D. A. (1986). The role of learning and coordination in strength training. European Journal of Applied Physiology and Occupational Physiology, 55, 100-105.

Ryushi, T., Hakkinen, K., Kauhanen, H., & Komi, P. (1988). Muscle fiber characteristics, muscle cross-sectional area and force production in strength athletes, physically active males and females. Scandinavian Journal of Sports Science, 10(1), 7-15.

Sale, D. G. (1988). Neural adaptation to resistance training. Medicine and Science in Sports and Exercise, 20(5), S135-S145.

Sale, D. & MacDougall, D. (1981). Specificity in strength training: a review for the coach and athlete. Canadian Journal of Applied Sport Science, 6, 87-92.

Schmidtbleicher, D., & Haralambie, G. (1981). Changes on contractile properties of muscle after strength training in man. European Journal of Applied Physiology and Occupational Physiology, 46, 221-228.

Starkey, D. B., Pollock, M. L., Ishida, Y., Welsch, M. A., Brechue, W. F., Graves, J. E., & Feigenbaum, M. S. (1996). Effect of resistance training volume on strength and muscle thickness. Medicine and Science in Sports and Exercise, 28(10), 311-1320.

Staron, R. S., Karapondo, D. L., Kraemer, W. J., Fry, A. C., Gordon, S. E., Falkel, J. E., Hagerman, F. C., & Hikida, R. S. (1994). Skeletal muscle adaptations during early phase of heavy-resistance training in men and women. Journal of Applied Physiology, 76(3), 1247-1255.

Stephens, J. A., & Taylor, A. (1972). Fatigue of maintained voluntary muscle contraction in man. Journal of Physiology, 220, 1-8.

Stone, M. H., O'Bryant, H., & Garhammer, J. (1981). A hypothetical model for strength training. Journal of Sports Medicine, 21, 342-351.

Tesch, P. A. (1992). Training for bodybuilding. In P. V. Komi (Ed), Strength and Power in Sport (pp. 370-380). London: Blackwell Scientific Publications.

Van Oteghen, S. L. (1975). Two speeds of isokinetic exercise as related to the vertical jump performance of women. Research Quarterly, 46(1), 78-84.

Weiss, L. W., & Clark, F. C. (1987). Journal of Sports Medicine and Physical Fitness, 27, 128-133.

Westcott, W. L. (1989). Strength Fitness: Physiological Principles and Training Technique. Dubuque. IA: Wm. C. Brown.

Wilson, G. J. (1994). Strength and power in sport. In J. Bloomfield, T. R. Ackland, & B. C. Elliot (Eds.) Applied Anatomy and Biomechanics in Sport, (pp.110-208). Melbourne: Blackwell Scientific Publications.

Wittekopf, G., Schaaf, E., & Taubenheim, H. Use of electromyography for quantification of local muscular fatigue following a known strength-endurance load. In E. Asmussen & K. Jorgensen (Eds.), Biomechanics VI: proceedings of the Sixth International congress of Biomechanics, Copenhagen, Denmark (pp. 185-193). Baltimore: University Park Press.

Young A., Stokes, M., Round, J. M., & Edwards, R. H. T. (1983). The effect of high-resistance training on the strength and cross-sectional area of the human quadriceps. European Journal of Clinical Investigation. 13, 411-417.

Young, W. B., & Bilby, G. E., (1993). The effect of voluntary effort to influence speed of contraction on strength, muscular power, and hypertrophy development. Journal of Strength and Conditioning Research, 7, 172-178.

Appendix A

Literatue Review

Increased expression of force relates to changes in the neuromuscular system. Changes may be related to the nervous system and the recruitment of motor units and the frequency of motor unit activation. Morphological changes in the muscle, such as increased muscle CSA or increased connective tissue, may also occur. The amount of tension applied to the musculature during training results in the changes that occur. Depending on how tension is applied, there can be increased maximal strength and/or hypertrophy, although it is difficult to identify an exact stimulus that will produce one or the other of these changes.

The time that the muscles are under tension within a training session has not been investigated to any great extent and thus its role as a training stimulus variable warrants further investigation. This review will focus on the status of human subject research involving isokinetic and isotonic studies that have considered the effects of time under tension on maximal strength and hypertrophy.

Neuromuscular changes in untrained individuals and the time course of these changes will also be discussed as this has bearing on the studies that have investigated time under tension. Neural responses to training will be briefly mentioned. This will include the effects of time under tension on motor unit recruitment which has important implications in neural and hypertrophic responses to time under tension.

Application of a Training Stimulus for Maximal Strength and Hypertrophy

Depending on the goals of resistance training, (absolute strength, relative strength, power, hypertrophy, or muscular endurance) the training stimulus can be applied in a number of ways including manipulation of the repetitions, sets, intensity, type of muscle action (concentric, eccentric, or isometric), speed of the muscle action, exercise choice, exercise order, intra-/inter-session rest interval, and length of a training sessions. All of these variables have been investigated to varying degrees with different training modes (isometric, isotonic, and isokinetic).

Different ways of providing a training load in terms of repetitions and intensity can be placed on a continuum related to the maximum load that can be used to perform the repetitions to failure, or repetition maximum (RM). There is an inverse relationship between the number of repetitions that can be completed and the intensity or force required to perform the repetitions. As the number of repetitions that can be completed increases, the force decreases (Anderson & Kearney, 1982; Atha, 1981; McDonagh & Davies, 1984; Sale & MacDougall, 1981). The implication of this is that there is an optimum number of repetitions based on the desired training effect.

Despite this general relationship between repetitions and force, research has not clearly demonstrated that it is possible to differentiate between the development of maximal strength and hypertrophy, with both requiring a high amount of force and corresponding low repetitions (Anderson & Kearney, 1982; Dons, Bollerup, Bonde-Petersen & Hancke, 1979; Hakkinen, Komi, & Alen, 1985; Mikesky, Matthews, Giddings & Gonyea, 1989; Sale & MacDougall, 1981). Berger (1962a) compared 1, 2, and 3 sets of 2, 6, and 10 repetitions and found that 3 sets of 6 repetitions to be the optimum for the development of maximal strength. Berger, (1962b) later compared single sets of 2-12 repetitions and determined that 4-8 repetitions was the most effective in developing maximal strength. Similarily, Withers (1970) found that multiple sets of 3, 5, or 7 repetitions resulted in significant increases in 1 RM strength with no differences between the groups. O'Shea (1966) compared three sets of 2-3 RM, 5-6 RM, and 9-10 RM and reported significant increases in 1 RM strength for all groups with no significant differences among the groups. He also measured hypertrophy, determined through thigh girths, and found no differences between the groups. More recently, Chestnut (1995) reported no differences in maximal strength and hypertrophy with 4 and 10 RM training protocols. Tesch (1992) compared the differing training protocols typically followed by Olympic weightlifters and power lifters, against those of bodybuilders to demonstrate that repetitions may differ depending on the desired outcome of maximal strength or hypertrophy development. Lifters often train with very heavy loads and low repetitions to emphasize maximum strength, whereas bodybuilders often train with 6-12 repetitions for hypertrophy. However, lifters and bodybuilders both display considerable hypertrophy and thus it can not be said that the differing training protocols have differential effects on hypertrophy. Poliquin (1990) related the development of maximal strength to a combination of neural and hypertrophic responses. He suggested that for 1-5 repetitions there is an increase in relative strength through enhanced neural drive. Increased maximal strength as a result of hypertrophy will occur when 9-12 repetitions are performed and with 6-8 repetitions there will be both neural and hypertrophic responses. This remains to be substantiated. Other studies and reviews have suggested that 8 to 12 repetitions (Hedrick, 1995; Wilson, 1995; Young & Bilby, 1993) or from 8 to 20 repetitions (Garhammer, 1981; Palmieri, 1983; Stone & O'Bryant, 1983) will result in muscle hypertrophy.

It is usually considered by resistance training practitioners that multiple sets are required to provide an adequate training stimulus for hypertrophy. A number of recommended sets to produce muscle hypertrophy with 8 to 12 repetitions has been identified. These include: 3-4 sets (Hedrick, 1995); 4 sets (Young & Bilby, 1993); 3-5 sets (Fleck & Kraemer, 1987; McDonagh & Davies, 1984; Stone, O'Bryant & Garhammer, 1981); 3-6 sets (Willoughby, 1992); or even up to 8 sets (Poliquin, 1989). These recommendations may be more applicable to trained individuals that require intense loads for continued improvements than to less trained. With untrained individuals a single set of 8-12 repetitions may be sufficient to produce positive hypertrophic and strength changes (Starkey et al., 1995).

The Role of Tension in Strength and Hypertrophy Development

Tension is considered a critical factor in producing strength and hypertrophy since muscles grow in response to tension (Goldberg, Etlinger, Goldspink, & Jablecki, 1975). A "high degree" of muscle tension is a necessary stimulus for strength (Atha,1981). Muscle actions of low force or tension development are not necessarily conducive to the development of maximal force, and result in small increases in maximum strength (Anderson & Kearney, 1982; Dons, Bollerup, Bonde-Petersen & Hancke, 1979) and often provide an insufficient stimulus for muscle growth (Dons et al.; Sale & MacDougall, 1981; Hakkinen, Komi, & Alen, 1985). Although it remains to be clarified, it is believed by practitioners that hypertrophy requires lower tensions performed with higher repetitions than that required for the development of maximal strength. The role of the time that muscle is under tension on hypertrophy has been relatively unexplored.

The speed of a muscle action has an influence on how long the muscle is under tension. This is important as there is a relationship between the speed of a concentric muscle action and the resulting muscle tension. Slow movements are associated with the development of high tension, with a slow concentric muscle action producing a greater corresponding muscle tension than a faster movement (Poliquin, 1988).

Time Under Tension in Isometric and Isokinetic Studies

The duration of a muscle action, considered in this review as time under tension, is often specified in isometric and isokinetic training and testing. With isometric modes the time of the muscle action is the time under tension and it is used as a control variable to aid in study replication. Fatigue and motor unit activity have been frequently studied using an isometric mode (Bigland-Ritchie, Furbush, & Woods, 1986; Fujimoto & Nishizono, 1993; Garland, Enoka, Serrano & Robinson, 1994; Maton, 1981). Studies investigating maximum strength as well as hypertrophy have used an isometric training mode (Garfinkel & Cafarelli, 1992) or have utilized an isometric testing mode with the time of muscle action specified (Hakkinen & Komi, 1983; Hakkinen, Pakarinen, & Kallinen, 1992; Ryushi, Hakkinen, Kauhanen, & Komi, 1988).

With isokinetic modes, the set velocity determines the time under tension and it has been used as a control, dependent, and independent variable. Studies using isokinetic training and testing with velocity, or time under tension, as an independent variable have tended to focus on the specificity effects of various velocities on peak torque and/or power in lower limb musculature. One of the first studies to examine the effect of training velocity on force was that of Moffroid and Whipple (1970). Training was performed at a velocity that required approximately 5 or 1.7 seconds per muscle action. Testing occurred at seven different velocities. The conclusion of the authors was that speed of exercise was specific for force increases at and below the training speed.

Unfortunately comparisons between groups were not reported. Examination of their data indicates that the slow training group made the greatest increases in peak torque. Other investigations into the effects of various training velocities in isokinetic studies are somewhat equivocal but tend to support some degree of specificity of training and testing velocities. Coyle and Feiring (1980) concluded from their study of different training velocities, that increased peak torque was specific to training velocity and testing velocity, although testing was only conducted at the two training velocities. The time to complete each muscle action was approximately 1.5 sec and 0.3 sec. Similarily, Caiozzo, Perrine, and Edgerton (1981), using velocities that required approximately 1.0 and 0.4 sec per muscle action, reported that testing revealed significant improvements in peak torque of the slow group at all but the fastest of seven test speeds, whereas the fast training group had significant improvements only at the three fastest speeds. Between group differences were not reported but the slow training group appeared to have larger improvements. This may be related to the slow group performing more total work. More recently, Ewing, Wolfe, Rodgers, Amundson, and Stull (1990), using training velocities similar to the above mentioned studies that required 1.5 or 0.4 sec to complete a muscle action, reported significant improvements for each group at their respective training velocity. At an intermediate velocity both groups increased peak power but the increase was not significant. This study also examined hypertrophy of fiber types. Significant increases in type I and IIa fibre areas were found with no differences between groups. Another study that included slightly longer times under tension (2 and 1 sec per muscle action) found that slow training resulted in significantly greater increases in strength (Van Oteghen, 1975). Test velocity was not reported.

The investigation of Katch, Pechar, Pardew, and Smith (1975) differed from the above studies in that an upper body exercise was used as well as and a much longer time under tension (10 sec versus 2 sec or less in the four above studies) for the slow group. The fast group trained with 2 seconds to complete the muscle action. Total volume of work was equated between groups. No specificity of training and testing was found, both groups had significant increases in maximum force at both speeds. Significant increases in arm girths occurred, suggesting hypertrophy, with the slow group having a "two-fold" greater increase than the fast group.

The results of studies which have used isokinetic training and testing to examine the effects of varying time under tension tend to support some degree of specificity. The changes involved with increases in strength more frequently occur at or near the training velocity. There is some suggestion that slower training produces greater increases in maximum force expression. It is difficult to make any conclusions regarding hypertrophy. There are some similarities among these studies in that they involved untrained subjects, were short term in length, and used 2-3 sets of 8-20 repetitions (except for the study of Moffroid and Whipple (1970) in which subjects performed approximately 20 or 60 repetitions). The response to training of untrained subjects will be discussed below.

Time Under Tension in Studies Involving Free Weights

The amount of time that the muscles are under tension in studies using isotonic or free weights is rarely mentioned in the literature. Most frequently it is included as a control variable, especially in studies examining muscular endurance when repetition rate is given (Anderson & Kearney, 1982; Kramer, Leger, Patterson, & Morrow, 1994; Ratzin Jackson, Dickinson, & Ringel, 1990). From this, the time per repetition can be determined, but the distinction between the time for concentric and eccentric phases and the rest between muscle actions is not specified. Kuramoto and Payne (1995) gave the rate of the concentric and eccentric actions although the time is given as "counts" and not an actual time.

There have been few studies investigating maximal strength and/or hypertrophy that have used time under tension as a control variable. Starkey et al. (1995) investigated the effects of training volume on strength and hypertrophy with subjects performing one or three sets of 8-12 repetitions. Subjects were untrained women and men. All exercises were executed at a count of two for the concentric phase and a count of four for the eccentric phase with a "pause" between phases. Maximum isometric strength and hypertrophy measured by ultrasound did not differ between the training groups or between gender.

Meadors, Crews, and Adeyanju (1983) included time under tension in a study that compared three protocols which had one group performing isotonic exercises with repetitions at a ratio of three seconds each for the concentric and the eccentric phases, a second group utilized isokinetic exercises with a concentric:eccentric ratio of 1:1, and a third group performed isotonic exercises with no specified time to complete the muscle actions. Subjects were untrained women and the study lasted eight weeks. It is difficult to compare the three different groups as they differed in the number of repetitions, number of sets, intensity, exercises, and rest time. However, the slow isotonic group which trained with one set of 13 repetitions did not differ significantly in maximum strength or muscular fatigue from the other isotonic group which trained with three sets of 10 repetitions. All groups improved in all exercises except elbow flexion.

There have been a few free weight studies that have used time under tension as an independent variable to examine the resultant effects on strength, power, and hypertrophy. Palmieri (1987) compared three training groups of untrained men, for differences in maximum strength and leg power over 10 weeks. All groups performed the eccentric phase of the lift in four seconds and differed in the time for the concentric contraction. The fast group completed the concentric portion of the lift in three-quarters of a second or less. The slow group did the same movement in 2 sec or more, and the third group did the slow method for six weeks and the fast method for the last four weeks. The slow and fast groups were matched in repetitions and sets but differed in intensity, with the fast group using approximately 16 percent less weight than the slow group. During the last four weeks these two groups differed in repetitions, sets, and intensity. The combination group differed in repetitions and sets throughout the study. All groups had significant gains in power with no difference between the groups. As the transfer of strength to power was being examined, significance of changes in maximal strength was not calculated. The slow group did improve 25 percent versus 20 percent for the two other groups. No measure of hypertrophy was made.

The effects of varying time under tension on lower body strength, power, and hypertrophy responses in untrained men over 7-1/2 weeks were investigated by Young and Bilby (1993). Both groups performed identical training of four sets of 8-12 repetitions to failure three times a week. The training velocities were not given but the groups performed the eccentric phase in a similar manner and differed in the concentric phase from "slow and controlled" to "exploding as fast as possible". The two groups significantly improved in all measurements with no significant differences in gains for any parameter. The slow group had slightly greater gains in dynamic and static peak force whereas the fast group had slightly greater gains in the rate of force development. These results suggest some degree of specificity related to training speed may have occurred.

The only other study using free weights and examining the effects of time under tension also evaluated various strength and power performance measures of the lower body using untrained women as subjects (Harman, Morrissey, Frykman & Han, 1994).

Training consisted of 3 warm-up sets and 3 sets of 8 repetitions of squats performed three times a week for seven weeks. The fast group spent one second on each of the concentric and eccentric phases while the slow group took two seconds for each phase. As with the above two free weight studies, both groups improved similarly in maximum strength. Only the fast group improved significantly in some of the power tests suggesting that there was some degree of specificity in response to training. In this study the strength gains were greater than muscle hypertrophy and the authors conclude that neural changes must also have occurred, although they were not measured.

The results of the above three studies that have varied time under tension between groups indicate that fast or slightly slower training does not influence the development of maximal strength. The effect on hypertrophy is inconclusive as only one study included a measure of hypertrophy. The influence of even longer periods of time under tension remains to be investigated.

Response to Training in Untrained Subjects

It is important to note that the subjects in these three free weight studies were untrained subjects training for a short period of time (7-10 weeks). It is possible that the training status may have influenced the training response. Untrained individuals can make large increases in maximum strength during the early weeks of training. These initial strength gains in the first four to eight weeks of a heavy resistance training program often occur without structural changes in muscle and are attributed to neural factors because increases in strength are greater than increases in muscle size (Enoka, 1988; Ikai & Fukunaga, 1970; Moritani & deVries, 1979; Rutherford & Jones, 1986; Hakkinen, 1985; Sale, 1988; Young, Stokes, Round & Edwards, 1983). Neural changes can be quantified through recording EMG's which show an increase in electromyographic activity, and through changes in specific tension, or the ability of the nervous system to exert force per unit of muscle CSA. Morphological changes, especially that of hypertrophy in the CSA of the individual muscle fibers, play a major role in continued strength development as training continues (Ikai & Fukanaga, 1970; McDonagh & Davies, 1984; Komi, 1986). This can explain why the response of untrained subjects to different training protocols also tends to be fairly "generic" (Chestnut, 1995; Hakkinen; O'Shea, 1966), which makes it difficult to determine the effects of the different programs. Morphological changes within the muscle may be necessary for continued strength expression.

Effects of Time Under Tension on Motor Unit Recruitment

Neural factors involve the ability of the nervous system to activate motor units. There are many ways in which neural changes can manifest themselves: (a) There can be increased activation of the prime movers and better coordination of the activation of all relevant muscles which results in an increased ability to apply force, (b) changes in motor unit recruitment and firing patterns, including increased firing of motor units, an increased ability to keep higher threshold motor units activated, and coordination of motor unit recruitment can also occur (Sale, 1988), (c) decreased Golgi tendon organ inhibition might allow more forceful muscle action (Staron, et al., 1994; Wilson, 1994), and (d) psychological components, such as motivation or learning to ignore painful inhibitory sensory inputs, can also have a role in central nervous system control on motor pathways and muscle fibers (MacLaren, Gibson, Parry-Billings, & Edwards, 1989).

According to the size principle of motor unit recruitment (Mendell & Henneman, 1971), the activities of motor units are combined to produce the total tensions required of the muscle (Clamann, Gillies, Skinner & Henneman, 1974). Muscle tension can also be produced through rate coding, which is the rate at which neural impulses are conducted to the individual motor units of the muscle (Deschenes, 1989). A combination of recruitment and rate coding is responsible for smooth coordinated movements and force expression necessary to the task required of the muscle.

The activity of individual motor units during sustained submaximal contractions has been studied. Using isometric testing, Maton (1981) studied the activity of individual motor units at forces up to 75 percent of maximum, and found motor unit recruitment in the biceps brachii continued to occur. Garland, Enoka, Serrano and Robinson (1994) also recorded the activity of individual motor units in the biceps brachii and found that the maintenance of a submaximal contraction was due in part to recruitment of additional motor units. This provides a rationale to perform exercises slowly with tension on the muscles, as additional motor units can be potentially recruited. This could provide additional stimulus for neural and/or morphological changes.

Conclusions

It is difficult to separate the relative contributions of neural and hypertrophic factors in training for increased expression of force. Although there are recommendations, based on training studies and protocols, followed by resistance training practitioners on how to apply an appropriate training stimulus to emphasize neural changes or to stimulate hypertrophy, there are no definitive protocols. Various training parameters such as repetitions, sets, and intensity have been investigated but other program variables such as exercise order, exercise choice, and rest periods still require investigation. Tension is considered important for maximum strength and hypertrophy, but the effect of muscle actions longer than several seconds to complete on maximal strength and hypertrophy remains unexplored. There is anecdotal evidence that time under tension of 6-10 seconds, and even up to 30 seconds, per muscle action is more effective at stimulating hypertrophy than more "traditional" methods. Whether this is true or not requires further investigation.

REFERENCES

Anderson, T., & Kearney, J. T. (1982). Effects of three resistance training programs on muscular strength and absolute and relative endurance. Research Quarterly for Exercise and Sport, 53(1), 1-7.

Atha, J. (1981). Strengthening muscle. Exercise and Sport Science Reviews, 9. 1-73.

Berger, R. A. (1962a). Effect of varied weight training programs on strength. Research Quarterly, 33(2), 161-181.

Berger, R. A. (1962b). Optimum repetitions for the development of strength. Research Quarterly, 33(3), 334-338.

Bigland-Ritchie, B., Furbush, F., & Woods, J. J. (1986). Fatigue of intermittent submaximal voluntary contractions: central and peripheral factors. Journal of Applied Physiology, 61(2), 421-429.

Caiozzo, V. J., Perrine, J. J., & Edgerton, V. R. (1981). Training-induced alterations of the in vivo force-velocity relationship of human muscle. Journal of Applied Physiology: Respirational, Environmental and Exercise Physiology, 51(3), 750-754.

Clamann, H. P., Gillies, J. D., Skinner, R. D., & Henneman, E. (1974). Quantitative measures of a motorneuron pool during monosynaptic reflexes. Journal of Neurophysiology, 37, 1328-1337.

Chestnut, J. L. (1995). The effects of 4RM and 10RM weight training protocols on strength, cross-sectional area, and specific tension in untrained males. Unpublished master's thesis, University of Victoria, Victoria, British Columbia, Canada.

Coyle, E. F., & Feiring, D. (1980). Muscular power improvements: specificity of training velocity [Abstract]. Medicine and Science in Sports and Exercise, 12(2), 134.

Deschenes, M. (1989). Short review: Rate coding and motor unit recruitment patterns. Journal of Applied Sport Science Research, 3(2), 33-39.

Dons, B., Bollerup, K., Bonde-Petersen, F., & Hancke, S. (1979). The effect of weight-lifting exercise related to muscle fiber cross-sectional area in humans. European Journal of Applied Physiology and Occupational Physiology, 40, 95-106.

Enoka, R. M. (1988). Muscle strength and its development. New perspectives. Sports Medicine, 6, 146-168.

Ewing, J. L., Wolfe D. R., Rogers, M. A., Amundson, M. L., & Stull, G. A. (1990). Effects of velocity of isokinetic training on strength, power, and quadriceps muscle fibre characteristics. European Journal of Applied Physiology and Occupational Physiology, 61, 159-162.

Garfinkel, S., & Cafarelli, E. (1992). Relative changes in maximal force, EMG, and muscle cross-sectional area after isometric training. Medicine and Science in Sports and Exercise, 24(11), 1220-1227.

Garland, S. J., Enoka, R. M., Serrano, L. P., & Robinson, G. A. (1994). Behavior of motor units in human biceps brachii during a submaximal fatiguing contraction. Journal of Applied Physiology, 76(6), 2411-2419.

Goldberg, A. L., Etinger, J. D., Goldspink, D. F., & Jablecki, C. (1975). Mechanism of work-induced hypertrophy of skeletal muscle. Medicine and Science in Sports and Exercise, 7(4), 248-261.

Hakkinen, K. (1985). Factors influencing trainability of muscular strength during short term and prolonged training. National Strength and Conditioning Association Journal, 7(2), 32-37.

Hakkinen, K., Komi. P. V., & Alen, M. (1985). Effect of explosive type strength training on isometric force- and relaxation-time, electromyographic and muscle fibre characteristics of leg extensor muscles. Acta Physiologica Scandinavica, 125, 587-600.

Hakkinen, K., & Komi, P. V. (1983). Electromyographic changes during strength training and detraining. Medicine and Science in Sports and Exercise, 15(6), 455-460.

Hakkinen, K., Pakarinen, A., & Kallinen, M. (1992). Neuromuscular adaptations and serum hormones on women during short-term intensive strength training. European Journal of Applied Physiology and Occupational Physiology, 64(2), 106-111.

Harman, E., Morrissey, M, Frykman, P, & Han, K. (1994). Differential training effects of barbell squat exercise performed at normal and fast speeds [Abstract]. National Strength and Conditioning Association Journal, 18(2), 196.

Hedrick, A. (1995). Training for hypertrophy. National Strength and Conditioning Association Journal, June, 22-29.

Ikai, M., & Fukunaga, T.(1970). A study on training effect on strength per unit cross-sectional area of muscle by means of ultrasonic measurement. International Zeitschrift fur angewandte Physiologie einschliesslich Arbeitsphysiologie, 28, 173-180.

Jackson, C. G. R., Dickinson, A. L., & Ringel, S. P. (1990). Skeletal muscle fiber area alterations in two opposing modes of resistance-exercise training in the same individual. European Journal of Applied Physiology and Occupational Physiology, 61, 37-41.

Katch, F. I., Pechar, G. S., Pardew, D., & Smith, L. E. (1975). Neuromotor specificity of isokinetic bench press training in women [Abstract]. Medicine and Science in Sports and Exercise, 7(1), 77.

Kramer, J. F., Leger, A., Patterson, D. H., & Morrow, A. (1994). Rowing performance and selected descriptive, field, and laboratory variables. Canadian Journal of Applied Physiology, 19(2), 174-184.

Kuramoto, A. K., & Payne, V. G. (1995). Predicting muscular strength in women: a preliminary study. Research Quarterly for Exercise and Sport, 66(2), 168-172.

Maclaren, D. P. M., Gibson, H., Parry-Billings, M., & Edwards, R. H. T. (1989). A review of metabolic and physiological factors in fatigue. Exercise and Sport Science Reviews, 17, 29-66.

Maton, B. (1981). Human motor unit activity during the onset of muscle fatigue in submaximal isometric contraction. European Journal of Applied Physiology and Occupational Physiology, 46, 271-281.

McDonagh, M. J. N, & Davies, C. T. M. (1984). Adaptive response of mammalian skeletal muscle to exercise with high loads. European Journal of Applied Physiology and Occupational Physiology, 52, 139-155.

Meadors, W. J., Crews, T. R., & Adeyanju, K. (1983). A comparison of three conditioning protocols on the muscular strength and endurance of sedentary college women. Athletic Training, 18(3), 240-242.

Mendell, L. M., & Henneman, E. (1971). Terminals of single Ia fibers: location, density, and distribution within a pool of 300 homonymous motorneurons. Journal of Neurophyiology, 35, 171-187.

Mikesky, A. E., Matthews, W., Giddings, C. J., & Gonyea, W. J. (1989). Muscle enlargement and exercise performance in the cat. Journal of Applied Sport Science Research, 3(4), 85-92.

Moffroid, M. T., & Whipple, R. H. (1970). Specificity of speed of exercise. Physical Therapy, 50, 1692-1700.

Moritani, T., & deVries, H. A. (1979). Neural factors versus hypertrophy in the time course of muscle strength gain. American Journal of Physical Medicine, 58(3), 115-130.

O'Shea, P. (1966). Effects of selected weight training programs on the development of strength and muscle hypertrophy. Research Quarterly, 37(1), 95-102.

Palmieri, G. A. (1983). The principles of muscle fiber recruitment applied to strength training. National Strength and Conditioning Association Journal, 5(5), 22-24.

Palmieri, G. A., (1987). Weight training and repetition speed. Journal of Applied Sport Science Research, 1, 36-38.

Poliquin, C. (1988). Variety in strength training. Science Periodical on Research and Technology in Sport, 8(8) August.

Poliquin, C. (1989). Theory and methodology of strength training: How many repetitions per set should be done? Sports Coach, 13(1), 22-25.

Poliquin, C. (1990). Theory and methodology of strength training. In: NCCP Task 2 Readings, Ottawa, Canada: Coaching Association of Canada.

Rutherford, O. M., & Jones, D. A. (1986). The role of learning and coordination in strength training. European Journal of Applied Physiology and Occupational Physiology, 55, 100-105.

Ryushi, T., Hakkinen, K., Kauhanen, H., & Komi, P. (1988). Muscle fiber characteristics, muscle cross-sectional area and force production in strength athletes, physically active males and females. Scandinavian Journal of Sports Science, 10(1), 7-15.

Sale, D. G. (1988). Neural adaptation to resistance training. Medicine and Science in Sports and Exercise, 20(5), S135-S145.

Sale, D. & MacDougall, D. (1981). Specificity in strength training: a review for the coach and athlete. Canadian Journal of Applied Sport Science, 6, 87-92.

Starkey, D. B., Pollock, M. L., Ishida, Y., Welsch, M. A., Brechue, W. F., Graves, J. E., & Feigenbaum, M. S. (1996). Effect of resistance training volume on strength and muscle thickness. Medicine and Science in Sports and Exercise, 28(10), 1311-1320.

Staron, R. S., Karapondo, D. L., Kraemer, W. J., Fry, A. C., Gordon, S. E., Falkel, J. E., Hagerman, F. C., & Hikida, R. S., (1994). Skeletal muscle adaptations during early phase of heavy-resistance training in men and women. Journal of Applied Physiology, 76(3), 1247-1255.

Stone, M. H., O'Bryant, H., & Garhammer, J. (1981). A hypothetical model for strength training. Journal of Sports Medicine, 21, 342-351.

Tesch, P. A. (1992). Training for bodybuilding. In P. V. Komi (Ed), Strength and Power in Sport (pp. 370-380). London: Blackwell Scientific Publications.

Tesch, P. A., & Larsson, L. (1982). Muscle hypertrophy in bodybuilding. European Journal of Applied Physiology and Occupational Physiology, 49, 301-306.

Van Oteghen, S. L. (1975). Two speeds of isokinetic exercise as related to the vertical jump performance of women. Research Quarterly, 46(1), 78-84.

Willoughby, D. S. (1991). Training volume equated: A comparison of periodized and progressive weight training programs. Journal of Human Movement Studies, 21, 233-248.

Wilmore, J. H., & Costill, D. L. (1994). Physiology of Sport and Exercise. Champain, IL: Human Kinetics.

Wilson, G. J. (1995). Disinhibition of the neural system: Uses in programming, training and competition. Strength and Conditioning Coach, 3(3), 3-3.

Wilson, G. J. (1994). Strength and power in sport. In J. Bloomfield, T. R. Ackland, & B. C. Elliot (Eds.) Applied Anatomy and Biomechanics in Sport, (pp.110-208). Melbourne: Blackwell Scientific Publications.

Withers, R. T. (1970. Effect of varied weight-training loads on the strength of university freshman. Research Quarterly, 27, 110-114.

Young A., Stokes, M., Round, J. M., & Edwards, R. H. T. (1983). The effect of high-resistance training on the strength and cross-sectional area of the human quadriceps. European Journal of Clinical Investigation. 13, 411-417.

Young, W. B., & Bilby, G. E., (1993). The effect of voluntary effort to influence speed of contraction on strength, muscular power, and hypertrophy development. Journal of Strength and Conditioning Research, 7, 172-178.

Appendix B

Consent form

CONSENT FORM FOR PARTICIPATION IN THE STUDY ENTITLED, "EFFECT OF TIME OF CONCENTRIC MUSCLE ACTIONS ON STRENGTH, HYPERTROPHY, AND SPECIFIC TENSION IN RESISTANCE-TRAINED WOMEN"

This research project is studying the effects of different strength training programs on strength and muscle development in women. You have been informed that the purpose of the research is to study how different resistance training programs influence changes in strength and muscle growth. The research is being conducted by Ellen Gillies of the School of Physical Education at the University of Victoria. Your participation in the study will involve about three hours a week for nine weeks. The results of this research study may be published.

Your participation is completely voluntary and you can withdraw from the study at any time, without explanation. You have been informed that there is a risk of injury from weight training. You may experience some temporary muscle soreness but this would be no greater than what you would normally experience in your training. You have also been informed as to the possible benefits of your participation in the study. These include the opportunity to train in a group, to train under supervision, and to become stronger.

Any data collected in the study will remain confidential and will be kept in a locked filing cabinet in a secure place. Only the researcher will have access to the data. Your name will not be attached to any data sheets, and your anonymity will be assured by using a code number to identify results from individual subjects. The master list linking names and codes as well as the signed consent forms will be stored separately from any data and will be kept for a maximum of 5 years before being destroyed. If you withdraw from the study, your results will be maintained in the same manner as the rest of the data or you may request that your relevant data be destroyed.

You are free to withdraw your consent at any time and to discontinue participation in the study without consequences. Any questions that you may have concerning the research study or your participation in it, before or after your consent, will be answered by Ellen Gillies, School of Physical Education, University of Victoria, Box 1700, Victoria, BC, V8W 2Y2, 250-721-8635, or 250-472-3052.

You acknowledge that you have read and fully understood the consent form and agree to give your consent to participate in the study..

Name of Participant: ______________________ Date: __________

Signature of Participant: ______________________ Telephone: ________

Signature of Researcher: ______________________

VITA

Surname: Gillies Given Names: Ellen Maureen

Place of Birth: Cudworth, Saskatchewan, Canada

Educational Institutions Attended:

University of Regina	1978-1983
University of Victoria	1995-1997

Degrees Awarded:

B.Sc. (Distinction)	University of Regina	1983

Honours and Awards:

Petro Canada Coaching Scholarship	1995-1997

Effect of Time of Concentric Muscle Actions on Strength, Hypertrophy, and Specific Tension in Resistance-Trained Women

Author [redacted]
Ellen Maureen Gillies
September 30, 1997