ISOKINETIC AND WEIGHT STRENGTH TRAINING

IN YOUNG MEN AND WOMEN

THE EFFECT OF ISOKINETIC AND WEIGHT STRENGTH TRAINING

IN YOUNG MEN AND WOMEN

BY

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Abstract

Six males (M,21.2 ± 1.2 y) and 6 females (F,20.3 ± .8 y) trained, by random assignment, the elbow flexors of one arm on an isokinetic device (ID,Hydra-Gym,Belton,Texas) and the other arm on weight device (WD,Rubicon Ind.,Stoney Creek,Ont.). Training consisted of 5 sets of 10 maximal effort repetitions at the slowest velocity on the ID and 5 sets of 8-12 repetitions maximum on the WD, 3 times per week for 20 weeks.

Needle biopsy samples were obtained from biceps brachii before and after training and analysed for fibre type distribution and fibre area. CT scans were taken of the upper arm and analysed for bicep, brachialis and total flexor cross-sectional area. Strength measurements on both arms were taken at 2 week intervals through the training period on the ID (3 velocities) and the WD (1RM) as well as a Cybex dynamometer (@ 30,120,180,240°/s) and isometric dynamometer (ISD) (@ 75, 90, 105, 120, 135, 150, 165°). Contractile properties were obtained from isometric twitch measurements and analysed for peak torque (PT), time to peak torque (TPT), 1/2 relaxation time (1/2 RT), Maximum rate of torque development (MRTD) and maximum rate of torque relaxation (MRTR).

Fibre areas showed no change in absolute values (um^2) however relative fibre area increased (+12.1%, $p<.07$), the change being most evident in the Type II fibres (+20.8%, $p<.06$). Bicep area increased 9% following training. Brachialis area increased in absolute and relative (41%) terms with the largest increase in M and F trained on the WD ($p<.05$). Total flexor area increased significantly with no differences between gender or training mode. Cybex peak torque increased significantly in F (14.1%) but not in M after training. Strength measured on the WD and ID increased significantly in all conditions. WD and ID training produced similar increases in strength measured on the ID. Strength measured on the WD increased more with WD (102.9%) than ID (58.6%) training. M made greater absolute increases in strength on the WD (88.0 vs 69.8 N) and the ID (266.2 vs 236.8 N) than F, whereas F made greater relative strength increases on the ID (99.3 vs 44.3%), WD (116.0 vs 45.5%) and ISD (22.5 vs 6.5%) than M. PT increased at 14 weeks and remained elevated to some extent, post training. MRTD and MRTR followed the pattern of PT. No change was observed in TPT or 1/2 RT with training. It was concluded that: (1) WD training causes greater gains in training specific strength; (2) M make greater absolute but smaller relative increases in strength than F; (3) WD training is more effective in increasing muscle size than ID training; (4) F can make comparable absolute gains in muscle mass to M; (5) PT increased with training, in part because of increased muscle mass; (6) Training of this intensity and duration does not affect the time-related contractile characteristics of human muscle.

Forward

The initial intent in writing this thesis was to submit it in the form in which it might have been submitted for publication in a journal. Following data analysis and the realization of the volume of data collected, it became apparent that more than one publication may be derived from this material. Therfore, it was decided to divide the results and discussion along the format that the publications may take as well as write the introduction in the form it would take in publications. Section A will deal with the training mode comparison and section B will discuss the male and female responses to strength training. The methodology section will be common for both of these sections and the reader is invited to review the introduction, methods results and discussion in sequence in order to make the thesis more readable. As a separate section, the literature review is designed to give the reader an historical overview of strength training and strength training research, as well as describing the effects of strength training on the morphological and physiological properties of muscle.

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Chapter I

Introduction

A. Isokinetic and Weight Training

The effectiveness of various modes of resistance training apparatus has been debated for some time. Since the advent of "isokinetic" resistance, researchers (Thistle et al. 1967, Moffroid et al. 1969, Pipes and Wilmore 1975) have attempted to determine whether or not this type of resistance training is more effective than more conventional, weight resistance devices. Both have certain theoretical advantages for producing increases in muscle size and strength.

Isokinetic (constant velocity) resistance refers to a device that maintains a preselected velocity of movement through the range of motion, regardless of the force applied to it (Perrine, 1968). The resistance mechanism of an isokinetic device matches any force applied to it, thereby preventing acceleration beyond the set velocity. Therefore an isokinetic device "matches" the strength curve allowing for maximum resistance through the range of motion.

Weight devices provide a constant external load and therefore tension at the muscle level varies with acceleration and deceleration of the weight and changes in the external resistance arm of the weight and internal moment arm of the muscle about the axis of rotation of the joint. For these reasons, maximum muscular tension is only developed at a certain point through the range of motion. However, this type of resistance, in contrast to most isokinetic devices, also involves an eccentric (lengthening of the muscle under active tension) phase of contraction. Along with the additional work through this phase of contraction, more tension is developed per active motor unit (Bigland-Ritchie and Woods, 1976) which may induce greater physiological and morphological adaptation in the muscle.

The effectiveness of both modes of training has been demonstrated in previous studies (MacDougall et al. 1980, Costill et al. 1979). Relatively few studies, however, have compared the modes of exercise directly. Thistle et al. (1967), Moffroid et al. (1969) and Pipes and Wilmore (1975) did comparative studies, concluding that isokinetic resistance was the best form of training for increasing strength. These studies were limited to measurements of voluntary strength and limb girth. As well as this, the validity of the studies by Thistle et al. (1967) and Moffroid et al. (1969) can be challenged due to the fact that they used only isokinetic and isometric measurements of strength. This would tend to bias the results in favour of the groups whose training mode was the same as that of the testing mode. Therefore a comparison study, using both specific and non-specific voluntary strength measurements would provide an unbiased assessment of strength increases with isokinetic and weight training.

No studies have compared the effects of isokinetic and weight resistance training on muscle structure using techniques which allow for better definition of changes in gross muscle and muscle cell structure . The disadvantages of using limb girths as an index of hypertrophy are obvious. Since limb girths are comprised by a large proportion of non-contractile tissue, they are not sensitive to small changes in muscle mass and cannot distinguish differential responses in different muscle groups. Computerized tomography (CT) scanning on the other hand, can detect small changes in muscle mass as well as allowing for the analysis of hypertrophy in separate muscles. Examination of muscle tissue taken from biopsy samples allows for the study of changes in muscle fibre size, particularily with respect to different fibre types. Both of these techniques allow for greater definition in examining the response of human muscle to 2 different modes of strength training as well increasing our basic knowledge of the effect of strength training on muscle.

Few studies (Duchateau and Hainaut, 1984; Liberson and Asa, 1959; McDonagh, Hayward and Davies, 1983 Sale et al., 1983) have examined the effect of strength training on the involuntary contractile properties of human muscle. None of these have examined the effect of a long-term training program on the involuntary contractile properties of a large muscle group which has been strenuously trained by individuals such as bodybuilders. In a cross-sectional study, Sale et al. (1983) found prolonged contraction and relaxation times and greater twitch tension in the hypertrophied triceps surae of male bodybuilders. The question as to whether this adaptation occurs in the elbow flexors of subjects trained over a 6 month period remains to be answered. Apart from the comparison of training modes, the examination of the effect of strength training on the involuntary contractile properties of human muscle is deserving of study in itself.

B. Male and Female Responses to Strength Training

There is question as to whether the same type and degree of adaptation occurs in females and males during identical strength training programs. Factors such as gender differences in endogenous hormones and muscle fibre number may restrict the amount of adaptation that can occur in females. Few studies have examined this question. Moritani and deVries (1979) used male and female subjects in a strength training study but paid little attention to differences in results between the 2 groups. Wilmore (1974) found greater relative strength gains in females compared to males. O'Shea and Wegner (1981) observed the same absolute and greater relative strength gains in females exposed to the same 7 week training program as a group of males. The question as to the effectiveness of identical resistance training programs on males and females remains largely unresolved, particularily in the study of muscle and muscle fibre hypertrophy. Wilmore (1974) noted similar gains in absolute lean body mass and upper body girths in females compared to males. The limitations of girth and skinfold measurements for assessing changes in muscle mass are again obvious. CT scanning and the analysis of biopsy tissue permit more precise definition of these adaptations.

The increasing number of females, performing strength training both as athletes and recreationalists, and a lack of research in this area created the need for such a study. A secondary purpose in this study was to compare the training responses in males and females to identical strength training programs.

Chapter II

Review of Literature

Introduction

> "There are many stories of contests with wild beasts that recall the exploits of Samson, but the most characteristic exercise of the time was weight lifting. Milo practiced it on most scientific principles with a young bull calf which he lifted day by day till it was fully grown."
>
> (Gardiner, 1930, pg. 54)

The story of Milo of Croton (circa 540 B.C.) is a familiar one and, as this quote suggests, man's preoccupation with strength and weight lifting is ancient. Accounts of contests and feats of strength dating back to 2500 B.C. can be found in many countries of the ancient world (Massey et al., 1959) and, since this time, man has been looking for effective ways of increasing strength and muscle mass whether it be for athletic performance or rehabilitation of injured joints and injured or atrophied muscle. Since the 1940's, significant advances have been made in the development of sound strength training methods and devices. It is the purpose of this review to document the development of strength training methods as we know them today. As well, the scientific study of the adaptations which occur with strength training, particularly in humans, has been revolutionized through the development of the needle biopsy technique and electrophysiological techniques to assess changes occurring within the muscle in response to strength training. This paper will also document studies which have examined the effect of strength training and different strength training modes on the structural and contractile properties of muscle.

A. Historical Perspective

Reseachers have examined the effects of strength training on skeletal muscle since the late 19th century. Early work was carried out in human and animal subjects, examining the effects of a variety of variables on strength and muscle morphology. In a series of experiments, Lombard (1892) studied the effect of factors from training to barometric pressure and alcohol consumption on his own strength and work output. Throughout the first part of this century other researchers noted effects such as specificity in strength gains, increases in muscle girths with high intensity, but not low intensity work and retention of strength in detraining (Steinhaus, 1933).

Early investigation into the effects of training on skeletal muscle morphology exclusively used animal models. These studies examined the effects of such perturbations as treadmill running and electrical stimulation upon muscle hypertrophy and fibre hyperplasia, enzyme changes and the onset of rigor mortis (Steinhaus, 1933).

The study of strength training using a defined system of resistance exercise, began in the 1940's. At this time, studies dealt primarily with rehabilitation and were conducted by physical medicine specialists. This, no doubt, came in response to the war-wounded who were being returned to their countries in need of rehabilitation. The development of strength training methods will be reviewed in the next section.

The study of cross transfer of training effects came under scrutiny at this time by rehabilitation specialists. Hellebrandt, Houtz and Parrish (1947) studied the cross- transfer of training phenomenon, with the aim of applying it to the maintainance of strength in immobilized and injured limbs. Cross transfer effects have since been examined in detail (Hellebrandt, Houtz and Parrish, 1947; Rasch and Morehouse, 1957), its degree of specificity (Gardner, 1963) and the extent to which it is retained during detraining (Shaver, 1975).

With the advent of this work in strength training, researchers began to examine the mechanisms behind the observed gains in strength and other concomitant adaptations in subjects exposed to this type of exercise. Delorme, Ferris and Gallagher (1952) examined the effect of strength training on voluntary contraction time. McMorris and Elkins (1954) attempted to link increases in strength with muscle hypertrophy as reflected by limb girth.

B. Development of Strength Training Methods

Documentation of systematic strength training programs dates back to the mid 19th century when individuals such as Charles Beck and George Winship presented treatises on strength development through weight lifting (Rasch, 1962). In 1902, Alan Calvert revolutionized strength training through the invention of the plate loading barbell as well as the publication of the "double-progressive" training method which was, in many respects, similar to the "progressive overload" method proposed by Delorme in 1945.

The first scientifically recognized approach to strength training was proposed by Thomas Delorme (1945) - an orthopedic surgeon concerned with the rehabilation of knee injuries (Rasch, 1962). His method involved the use of progressively increasing weight resistance across 3 sets of exercise. Resistance was successively increased from 50 to 75 and then to 100 % of the 10 repetition maximum (10RM-the most weight that could be lifted ten times) value with 10 repetitions performed per set. Delorme (1945) stressed the need to monitor and progressively increase the resistance as the subject became stronger, terming it "progressive resistance exercise". Also stressed was the need to differentiate strength and endurance training in order to determine the most appropriate type of training for rehabilitation, as the results of each are mutually exclusive. This exercise system was successful in rehabilitating a variety of orthopedic problems and soon came to be known as the "Delorme technique of progressive resistance exercise" (Delorme and Watkins, 1947).

A variation of this technique was proposed by Zinovief (1952 in McMorris and Elkins, 1954) and came to be known as the "Oxford" technique. It involved beginning the exercise at 100% of the 10RM value for 10 repetitions and progressively decreasing the weight with every set performed. This technique was compared to that of Delorme by McMorris and Elkins (1954) who found significant gains in muscle strength and limb girth using both techniques. This princple of progressive resistance was subsequently demonstrated experimentaly by Hellebrant and Houtz (1956).

Both of these techniques used weights as the form of resistance in the exercise. In the 1950's, isometric contraction was introduced as a means of increasing strength and muscle size. Isometrics involves exerting force against an immovable object such that tension is developed in the muscle although no external movement occurs. Its advantage was that it could be carried out without elaborate equipment. Significant gains in strength are possible using isometric resistance; however, subsequent research on the subject has shown that gains in strength are mainly confined to that mode of contraction (Darcus and Salter, 1955; Berger, 1962a) as well as to the joint position at which the training was performed (Gardner 1963). Therefore the application of isometric strength gains are limited in a practical sense.

Isometric exercise was extensively studied by Muller and Hettinger in the 1950's. They observed significant increases in isometric force during a training period using 4-6s of isometric contraction at 66% of maximum force with no additional increase in strength with increases in training intensity (Hettinger and Muller, 1953). Muller (1962) subsequently reviewed their early work, concluding that greater increases could be attained by increasing the intensity but not the duration of training contractions. Since then researchers have not found as impressive gains using this form of resistance activity (Moritani and deVries, 1978; McDonagh, Hayward and Davies, 1983). Early studies comparing isometric and weight resistance exercise found greater increases in isometric and dynamic strength with weight training (Darcus and Salter, 1955; Rasch and Morehouse, 1957).

Isometric exercise has been used in the rehabilitation of immobilized limbs as well as studies of the physiological effects of strength training (e.g. McDonagh, Hayward, Davies, 1983); however, it never was regarded as an effective strength training method for athletic events. An exception to this is the isometric strength skills associated with gymnastics. Strength gains obtained through isometric and weight resistance training have been reviewed by McDonagh and Davies (1984)

The concept of isokinetic resistance was developed in the late 1960's by James Perrine, an engineer. The concept of this type of resistance is that of controlling the velocity of contraction of a movement. If a maximal contraction is performed resistance should be maximal through the range of motion, strengthening the muscle group at every point in its shortening range (Hislop and Perrine, 1967). Velocity is controlled at a preset value using a speed governing device. The load in this type of exercise is not gravity or friction but mechanical energy absorption by the isokinetic device.

This approach was designed to offset some of the theoretical disadvantages of weight resistance. It is known that muscle strength varies through the range of motion due to the length-tension relationship in skeletal muscle as well as changes in the "angle of pull" of a muscle about the axis of rotation of the joint (Singh and Karpovich, 1967). Also, the external resistance of a weight changes throughout the range of motion, depending upon the resistance moment arm of the weight. Acceleration can also vary the resistance applied by a weight. At the beginning of a lift, when acceleration is occuring, the force applied to the mass must be greater than its weight. At the end of the movement, when deceleration is occuring, the force applied to the mass is less than its weight. Because of these factors, muscle tension is maximal only at a certain point in the range of motion and muscle is only trained at the point of its greatest mechanical disadvantage or "weakest point".

Isokinetic resistance was immediately hailed by physical medicine specialists as providing a more safe and effective means of increasing strength (Thistle et al., 1967; Moffroid et al.,1969). It has been shown by numerous studies to be effective in increasing strength (Coyle et al.,1981; Costill et al., 1979; Kanehisa and Miyashita, 1983a; Komi and Buskirk, 1972; Krotkiewski et al., 1979; Mannheimer, 1969; Seaborne and Taylor, 1982) and many studies have used the isokinetic device to examine specificity of velocity with strength training (Adeyanju, Crews and Meadors, 1978; Coyle et al., 1981; Kanehisa and Miyashita, 1983b; Lesmes et al., 1978; Moffroid and Wipple, 1970) because the isokinetic device is perfectly suited to the study of this phenomenon (for a review of specificity see Sale and MacDougall, 1981).

Few of these studies have examined changes in muscle or fibre morphology with isokinetic training. Costill et al. (1979) found no significant change in leg girth following 6 weeks of isokinetic training. To this author's knowledge, no studies have examined changes in muscle areas with isokinetic training using CT scanning or ultrasound. Some studies using isokinetic training have observed increases in muscle fibre area with training (Krotkiewski et al., 1979) while others have not (Costill et al. 1979; Coyle et al., 1981; Seaborne and Taylor, 1982).

Comparison studies of weight and isokinetic resistance training have tended to show greater increases in strength with isokinetic training (Thistle et al.,1967; Moffroid et al.,1969); however, these studies have tended to bias their results by only doing measures of strength on the isokinetic device. As well as this, comparison studies have neglected to examine changes in muscle size, muscle fibre area and involuntary tension and contractile properties of the muscle (see below).

Moffroid et al., (1969) completed one of the first comparative studies of isokinetic and weight resistance exercise. Three exercise groups trained the knee extensors and flexors. An isokinetic group performed 30 maximal repetitions (reps) at 22.5 °/s angular velocity. The weight resistance group utilized a progressive resistance protocol of 3 sets x 10 reps with the last set at maximum. The isometric group performed 10 maximal contractions at 90° flexion and 45° flexion.

Isometric (45 and 90°) and isokinetic peak torque measures were made before and after the 4 week training period. The isokinetic and isometric groups improved significantly in isometric peak torque. The weight resistance group showed significant improvement only at the 45° angle. In the isokinetic testing, the isokinetic group was the only group to improve significantly. It was concluded that isokinetic exercise was the preferred type of training for improving strength (Moffroid et al.,. 1969). A limitation of this study is that the greater strength improvement shown by the isokinetic group in isokinetic testing may be a result of specific neural adaptation to training devices as noted by Sale and MacDougall (1981). A weight resistance strength test may have shown greater improvements in the weight trained group than the other 2 groups.

These findings supported those of Thistle et al. (1967), who used the same protocol over a four week training period. Their results showed that the isokinetic group showed better improvement in total work capacity and peak torque as measured by the isokinetic dynamometer. The isokinetic group showed a 35.4 % increase in total work capacity and 47.2 % in peak torque compared to 27.5 % and 28.6 % improvements for the weight resistance group (Thistle et al.,. 1967). Conclusions made from these studies are questionable because testing was only done on with the isokinetic dynamometer.

The most recent study to compare isokinetic and weight resistance was done by Pipes and Wilmore (1975). High speed (136 °/s) isokinetic training produced greater gains in isokinetic and weight resistance strength. Increased limb girths were observed with both isokinetic and weight resistance training. Since the publication of this study the senior author has withdrawn his association with the study recognizing that the data were falsified, bringing into question the validity of the study.

C. Females and Strength Training

Few studies have addressed the question of the effectiveness of identical strength training programs in males and females. Studies have used males and females as subjects but have not bothered to report differential results (Young et al., 1983). Studies using females as subjects have reported significant gains in strength (Brown and Wilmore, 1974; Seaborne and Taylor, 1982; Krotkiewski et al., 1979; Kaufmann, 1985; Krahenbul, Archer and Petit, 1978; Oyster, 1979) ranging from 20% to 100% over periods of 6 to 7 weeks.

The few comparative studies which have been done have tended to show greater capacity for relative strength gains in females. Wilmore (1974) found greater relative strength gains in college-age females after a 10 week weight training program and Wilmore et al. (1978) observed greater absolute and relative increases in strength in females after 10 weeks of circuit weight training in the same population. The males and females made similar gains in lean body mass. The same results were found by O'Shea and Wegner (1981) in females trained using heavy bench press and squat exercises over a 7 week period.

In terms of changes in muscle morphology, Krotkiewski et al. (1979) have shown increases in muscle mass in females as reflected by ultrasound, accompanied by increases in Type II fibre areas. Young et al. (1983) reported increases in fibre areas with strength training in a group of male and female subjects but did not discriminate between genders. Seaborne and Taylor (1982) found no increase in fibre areas of females exposed to 5 weeks of strength training. Wilmore in 1974 and with coworkers in 1978 found significant increases in limb girths due to training while others have found no change in muscle mass as reflected by limb girths following strength training in females (Krahenbul, Archer and Petit, 1985; Oyster, 1979; Brown and Wilmore, 1974). Moritani and deVries (1979) reported that absolute gains in elbow flexor cross-sectional area were 47% greater in college age males than in females.

D. Muscle Hypertrophy

Given the same conditions (ie. contraction type) and subjects with the same level of training, muscle strength has been shown to be highly correlated to muscle cross-sectional area in humans (Schantz et al. 1983) and stimulated animal muscle preparations (Close, 1972), the result being a relatively constant strength or tension per unit cross-sectional area (for review and ref. see Maughan,1984). Hence, an increase in cross-sectional area brought about by resistance training should be related to the observed increases in tension development in the trained muscle. It is well known that neural factors contribute a great portion of the gains in strength observed, particularily during the early phases of training (Moritani and deVries, 1978) however this review is concerned with adaptations occurring within the muscle itself (For a review of neural adaptations to strength training, see Sale, 1986).

1. Animal Studies

Evidence of muscle hypertrophy due to functional overload is well documented in both human and animal studies. In animal studies, primarily 2 models have been used, one involving the elimination of the synergists of a certain muscle in order to increase the mechanical stress on that muscle (compensatory hypertrophy) and the second involving training the animal with a high resistance low repetition activity using a reward (Gonyea and Ericson, 1976) or avoidance (Gordon, Kowalski and Fritts, 1967) stimulus. Questions as to the appropriateness of the former have arisen (Gonyea et al., 1986), as it represents a transient overload stimulus which is not characteristic of the "progressive overload" nature of strength training or rehabilitation exercise. A third less common model is that of stretch induced hypertrophy caused by hanging weights on an animal's limb (Sola, 1973) or fixing a muscle in an extended position (Barnett, Holly and Ashmore, 1981).

Studies examining hypertrophy in animal models commonly excise whole muscles for assessing changes in weight, muscle morphology and biochemistry and therefore give an indication of changes in the whole muscle. Studies using the compensatory hypertrophy model have demonstrated significant gains in muscle mass over relatively short time periods (Gollnick et al., 1981; James, 1973; Reitsma, 1969; Rowe, 1969; Roy et al., 1982; Schiaffino and Bermoli, 1973). This gain in muscle mass has been identified as an increase in tissue protein

(Goldberg et al., 1975). The increase in muscle mass has been shown to be inversely related to the percentage of the original muscle mass remaining following the surgical intervention (ie. ablation of synergists) (Reitsma, 1969). Increases ranging from 16% in the non exercised rat extensor digitorum longus (James 1973) to 151% in the exercised rat soleus (Reitsma, 1969) have been observed in as little as 60 days. The increased muscle weight has been shown to increase the muscle's tension producing capabilities under twitch (Goldberg et al., 1975; Roy et al., 1982) and tetanic stimulation conditions (Goldberg et al., 1975; Rowe, 1969; Roy et al., 1982). Goldberg et al. (1975) reported that the increased muscle protein content was primarily in the sarcoplasmic fraction; however, the increased tension producing capabilities found by those authors as well as Roy et al. (1982) would suggest that a significant increase in myofibrillar protein occurred as well.

The model of stretch induced hypertrophy in the chicken wing has also demonstrated significant increases in muscle mass (Sola, Christenson and Martin, 1973; Gollnick, 1983; Holly et al., 1981; Barnett, Holly and Ashmore, 1981). The increase in tissue protein synthesis in this model has been found to occur largely outside the muscle basement membrane (Barnett, Holly and Ashmore, 1981) and therefore is primarily involved in connective tissue protein synthesis although an increase in muscle cell nuclei has also been observed (Sola, Christenson and Martin 1973). None of these studies has measured muscle tension producing capabilities; however, Holly et al. (1981) observed no change in EMG of the stretch hypertrophied, chicken anterior lattisimus dorsi muscle indicating a lack of functional change in the muscle.

A more representative model of muscle hypertrophy in animals is the performance of heavy resistance exercise by the animal. Significant increases in muscle mass have been observed in weight lifting mice (Goldspink, 1964), rats (Gordon, Kowalski and Fritts, 1967b), hamsters (Goldspink and Howells, 1974), "lesser bushbabies" (Edgerton, 1976) and the cat (Gonyea and Ericson , 1976; Gonyea, Ericson and Bonde-Petersen, 1977; Gonyea, 1980; Gonyea et al., 1986). This increase in muscle mass has been shown to be due to an increased myofibrillar protein fraction (Gordon, Kowalski and Fritts, 1967b; Edgerton, 1976). Greater voluntary weight lifting performance (Edgerton,1976; Gonyea 1980) and involuntary muscle tension producing capabilities (Edgerton,1976; Gonyea and Bonde-Petersen, 1978) have been observed along with these increases in muscle mass.

2. Human Studies

a. Cross-Sectional Studies

Evidence of gross muscle hypertrophy is evident from observations of those who have participated in strength training for a considerable length of time. A whole industry has grown up around "body building" and the promotion of muscle growth. These observations have also been documented in cross-sectional studies measuring the size of a muscle group in strength-trained and control subjects. Studies have shown greater muscle areas in the upper arm, as reflected by girths (MacDougall et al., 1982) and computerized tomography scanning (triceps brachii, Schantz et al., 1983; elbow flexors, MacDougall et al., 1984; Schantz et al., 1983) in bodybuilders. Greater areas have also been observed in the leg extensor muscles of weight trainers using CT scanning (Haggmark, Janson, Svane, 1978; Schantz et al., 1981; Schantz et al., 1983). CT scanning is extremely useful in studies assessing hypertrophy because it can detect changes in the size of a specific muscle group independent of subcutaneous fat. Ultrasound has also been used and can differentiate between lean tissue and fat; however, the sensitivity of this method has been questioned (Schantz et al., 1983).

b. Longitudinal Studies

Increases in limb girths have been found in strength training studies involving the leg extensors (Young et al., 1983; Hakkinen, Alen and Komi, 1985), elbow extensors (McMorris and Elkins, 1954; Rasch and Morehouse, 1956; MacDougall et al., 1977) and elbow flexors (Delorme et al. 1952; Hettinger and Muller, 1953; Komi and Buskirk, 1972; Moritani and deVries, 1978). These studies have employed weight resistance (Hakkinen, Alen and Komi, 1985; MacDougall et al., 1977; Young et al., 1983; McMorris and Elkins, 1954; Rasch and Morehouse, 1956; Delorme et al., 1952) as well as isometric resistance (Moritani and deVries, 1978; Hettinger and Muller, 1953) and isokinetic (hydraulic) resistance (Komi and Buskirk, 1972). Other studies have shown no change in limb girth (Thorstensson et al., 1976; Costill et al., 1979; Coyle et al., 1981; McDonagh, Hayward and Davies, 1983) but significant increases in strength. Three of these investigations studied the leg extensors in males and 2 of these studies (Costill et al., 1979; Coyle et al., 1981) used isokinetic resistance as the form of training. McDonagh, Hayward and Davies (1983) showed no increase in upper arm girths following 5 weeks of isometric training for the elbow flexors. The limitations of girth measurements are obvious and are probably accentuated in these short term studies.

Longitudinal studies have also used ultrasound to measure changes in muscle size. Ikai and Fukunaga (1970) observed a 23% increase in elbow flexor area following 100 days of isometric training. Krotkiewski et al. (1979) and Young et al. (1983) have observed increases in leg muscle thickness and cross-sectional area (respectively) using five weeks of isokinetic (Krotkiewski et al., 1979) and weight training (Young et al., 1983).

E. Muscle Fibre Hypertrophy

The long held assertion that muscle hypertrophy caused by training is a result of growth of individual fibres (Siebert, 1928) has been studied in the animals and humans (cross-sectionally and longitudinally).

1. Animal Studies

Studies using the compensatory hypertrophy model in animals have observed increases in the size of existing fibres as reflected by fibre diameter (James, 1973), fibre weight (Gollnick et al., 1981) or fibre area (Rowe, 1969; Roy et al., 1982). Muscle fibre hypertrophy has also been demonstrated in chronically stretched muscle (Gollnick et al., 1983; Holly et al., 1980; Barnett, Holly and Ashmore, 1980; Sola, 1973)

A more representative model of strength training is that of weight lifting animals. Fibre hypertrophy has been identified in all studies using weight lifting exercise in animals (Edgerton, 1976; Goldspink, 1964; Goldspink and Howells, 1974; Gonyea and Ericson, 1976; Gonyea and Bonde-Petersen, 1977; Gonyea, 1980). Increases in fibre area have been observed to be greatest in "white" (Gordon, Kowalski and Fritts, 1967b) or fast glycolytic and fast oxidation glycolytic (Edgerton, 1976) fibres indicating a greater potential for adaptation in these fibres.

The increase in fibre size in animals has been shown to be caused by an increase in the size (Rowe, 1969) and number (Goldspink, 1964) of myofibrils. This agrees with the observation of greater myofibrillar protein fraction found in other studies (Edgerton, 1976; Gordon, Kowalski and Fritts, 1967b).

2. Human Studies

Human studies have used cross-sectional as well as longitudinal studies to assess fibre hypertrophy. The only limitation of human studies being that whole muscles cannot be excized and therefore one must rely on a relatively small biopsy sample to provide a representative sample of fibre areas in the tissue.

a. Cross-Sectional Studies

Most cross-sectional studies comparing weight trained individuals with control subjects or other groups of athletes have shown greater fibre areas in the weight trained individuals (Costill et al., 1972; MacDougall et al., 1984; Prince et al., 1976; Tesch and Karlsson, 1985; Edstrom and Ekblom, 1972; Haggmark, Jansson, Svane, 1978; Schantz et al., 1981, 1983; Staron et al., 1984). These studies are supported by a limited autopsy study performed by Etemadi and Hossieni (1968) who found larger fibres in the biceps of an individual of "athletic build" compared to 2 age matched controls. Two other studies, however, have observed no difference in fibre area in body builders compared to untrained individuals (Tesch and Larsson, 1982) and to individuals who had only strength trained for 5 months (MacDougall et al., 1982) despite the fact that muscle size (girth) was considerably greater in the bodybuilders. The lack of difference in fibre area may be due to the variability observed in biopsy sampling. It is doubtful that fibre hyperplasia could account for this finding as the number of fibres in the muscle of strength trained individuals and untrained controls has been shown not to differ.

b. Longitudinal Studies

Longitudinal studies examining muscle fibre hypertrophy in humans have had mixed results. Some studies have shown increases in fibre area following strength training in the elbow extensors (MacDougall et al., 1980) and vastus lateralis (Hakkinen, Alen and Komi, 1985; Houston et al., 1983; Komi et al., 1982; Krotkiewski et al.,1979; Young et al.,1983) while others (Thorstensson et al., 1976;

Costill et al., 1979; Seaborne and Taylor, 1982; Coyle et al., 1981) have failed to show increases in fibre size with strength training. The latter studies all examined the vastus lateralis and all were done over a fairly short time period (6-7 weeks). It may be that the vastus is not as trainable as other muscle groups, particularily over such a short time period. Other studies have observed increases in fibre area using high, but not low speed isokinetic training (Coyle et al., 1981), light weight and plyometric training (Hakkinen, Komi and Alen, 1985), sprint (Thorstensson et al., 1975) and ice hockey training (Green et al., 1979). A common observation of cross-sectional and longitudinal studies showing fibre hypertrophy is that a greater amount of hypertrophy occurs in Type II fibres, supporting previously discussed work in animals (Edgerton et al., 1976; Gordon Kowalski and Fritts, 1967b) although Type I fibres are capable of significant growth as well (MacDougall et al., 1980; Young et al., 1983).

F. Muscle Ultrastructure

There is little information regarding the ultrastructural effects of strength training on muscle tissue; however, MacDougall et al. (1982) observed decreased myofibrillar and increased cytoplasmic volume density in the muscle fibers of body builders and power lifters. These athletes had been ingesting steroids which may have caused this excess of cytoplasm. Luthi et al. (1986) observed no change in the density of myofibrils, but a significant increase in absolute myofibrilar content in the muscle over a 6 week training period.

Increases in myofibril area along with incidence of splitting myofibrils have been observed (MacDougall, 1986) agreeing with previous work done in animals (Goldspink, 1964; Rowe, 1969) attributing increases in fibre area to an increase in myofibrillar protein. A common observation of strength training studies examining ultrastructure is a decrease in the volume density of mitochondria in the muscle, indicating a possible deleterious effect to endurance when muscle mass is increased with strength training (MacDougall et al., 1979; Luthi et al., 1986). The effects of strength training on muscle ultrastructure has been reviewed by Hoppeler (1986).

G. Mechanism of Hypertrophy

As to the mechanism of increases in muscle fibre size, it is evident that mechanical stress is a key factor in "turning on" muscle protein synthesis, and in particular myofibrillar protein synthesis. It has been evident from quite early research that this mechanical stress must be above that which is found in rhythmic dynamic activity (Siebert, 1928) and is probably greatest when a near maximal functional load is placed on the muscle. Some indirect evidence exists which may help explain how heavy resistance training initiates protein synthesis. Cell hypertrophy can be induced by simply stretching a muscle (e.g. Sola et al., 1973) or an isolated preparation of myoblasts (Vandenburg and Kaufman, 1979) indicating that muscle tension whether it be voluntary or involuntary can initiate protein synthesis as reflected by increases in muscle RNA concentrations (Goldberg et al., 1975). It should be mentioned, however, that stretch is a far different overload than that imposed by weight training which may act in a manner independent to that of stretch. Also, stress-induced hypertrophy has been shown to not be affected by alterations in blood plasma insulin, thyroxine, testosterone and amino acid concentration in the rat compensatory hypertrophy model (Goldberg et al., 1975). However, Gordon, Kowalski and Fritts (1967b) noted that gain in muscle mass in weight trained rats was limited due to a decrease in dietary intake. Therefore, although hormonal status may alter the growth of muscle as observed with anabolic steriod ingestion (e.g. Rogozkin, 1979), it does not provide the direct impetus for this increase in protein synthesis. Nutritional status may impair muscle growth (Gordon, Kowalski and Fritts, 1967b) but it is evident that fibre hypertrophy can still occur with decreased blood amino acid concentrations (Gordon, Kowalski and Fritts, 1967b; Goldberg et al., 1975). Stretch has been shown to increase amino acid transport into the muscle as well as increase intramuscular calcium levels, both of which have been implicated in increasing protein synthesis in isolated preparations (McDonagh and Davies, 1984). The induction of "tensile strain" in actin and myosin filaments has also been suggested as a possible mediator in increasing protein synthesis (McDonagh and Davies, 1984) and it may be that muscle damage caused by strength training causes an increase in protein synthesis and an "overshoot" in the amount of contractile protein laid down (MacDougall, 1986). Whatever the mechanism, it is evident that strength training produces an increase in muscle protein synthesis as reflected by increased RNA concentration as well as decreased protein degradation, the net effect being the accretion of protein in the strength trained muscle.

H. Muscle Fibre Hyperplasia

Although muscle fiber hypertrophy has been identified as a mechanism responsible for gross muscle hypertrophy in animals (Gollnick et al., 1981, 1983) and humans (MacDougall et al., 1980), there is question as to whether muscle is capable of hyperplasia. For many years it was assumed that the only avenue for muscle growth was through increases in fibre size (Morpurgo 1897 cited in Seibert 1928).

The majority of studies examining muscle hyperplasia is done in animals as it is possible to excise whole muscles to determine fibre number. The first work to identify the possibility of hyperplasia was the compensatory hypertrophy model in rats (Reitsma, 1969; Hall-Craigs, 1972; James, 1973). Reitsma (1969) surgically ablated muscles in the rat hind limb in order to impose varying degrees of stress on the remaining muscle mass. After 60 days of treadmill training, significant hypertrophy was observed in all muscles with considerable fibre splitting and fibre necrosis in the muscles put under the greatest stress. Hall-Craigs (1972) observed "clefts" in existing cells (indicating possible division), the seperation and rejoining of fibres and a proliferation of satellite cells in the muscle. James (1973) substantiated these findings in the same model and identified "satellite structures" which may be involved in hyperplasia. Hypertrophy along with increases in fibre number, splitting fibres, increases in fibre nuclei and the emergence of small "new" muscle fibres has also been identified in chicken wing muscle exposed to chronic stretch (Sola, 1973). Using the compensatory hypertrophy in the mouse soleus muscle, Vaughn and Goldspink (1979) observed increases in fibre number at the distal end of the muscle.

Although these studies documented evidence of muscle fibre hyperplasia, a systematic approach to its identification under physiological conditions was not undertaken until 1976. The use of surgical ablation in animals, although a useful model, is only a transient stress on the muscle and is not analogous to the progressive load used in strength training or rehabilitation. Gonyea and Ericson (1976) successfully trained cats to undergo heavy resistance exercise demonstrating increases in muscle size and fibre diameter in excised muscles from the trained cat limbs. Since this time, Gonyea and others have undertaken a number of studies on hypertrophy and hyperplasia in the exercising cats. Gonyea, Ericson and Bonde-Petersen (1977) showed significant increases (19%) in the number of fibres counted in total muscle sections of the cat flexor carpi radialis muscle (FCR). This was repeated by Gonyea (1980) who found 20.5% increases in fibre counts in the cat FCR but only in "high responder" cats who were able to lift more than 1 Kg.

This work was questioned by Gollnick et al. (1981, 1983) who demonstrated no increase in fibre number in either rat muscle stressed by surgical ablation (Gollnick et al., 1981) or chicken muscle exposed to prolonged stretch (Gollnick et al., 1983). These investigators determined fibre number with direct counts of fibres following nitric acid digestion. It was suggested, in these papers that the observed increases in fibre number by Gonyea, Ericson and Bonde-Petersen (1977) and

Gonyea (1980) were simply artifacts due to the increased angle of pennation in trained muscle fibres which would artificially increase the number of fibres seen in cross-section. Prior to this, Goldspink and Howells (1974) observed no change in fibre number of the EDL of weight trained hamsters while significant fibre hypertrophy occurred. Gonyea et al. (1986) have since used the nitric acid digestion with direct fibre counts in the trained cat FCR and demonstrated a 9% increase in fibre number over 101 weeks of training. This may be a more conclusive case for hyperplasia than Gollnick et al. (1981, 1983) have been able to mount against it as both of Gollnick's studies involved non-physiologic conditions over a relatively short (60 days) time period which most certainly does not approximate the stress of years of training.

Studies in humans by Tesch and Larsson (1982) and MacDougall et al. (1982) have suggested the possibility of fibre hyperplasia in subjects who have undergone years of strength training. Both of these studies observed large differences in muscle size between relatively untrained subjects and trained "body builders" with no difference in muscle fibre area. However, MacDougall et al. (1984) have calculated fibre number in biceps using CT scanning and fibre area measurements and found no differences in the number of fibres in the muscle of body builders compared with untrained control subjects. Recent work by Larson and Tesch (1986) using single fibre EMG levels has found greater fibre densities as reflected by increases in single fibre potentials, in 2 elite bodybuilder subjects. This would indicate a greater number of fibres per motor unit in these individuals. Larson and Tesch (1986) suggested hyperplasia of fibres in existing motor units as an explanation for this observation. Type grouping of motor units was rejected as an explanation for this finding as no electromyographic abnormalities were observed in the subjects (Larson and Tesch, 1986)

The common observation in several of these studies of the large number of small fibres and greater variability in fibre areas in chronically trained muscle has led some to speculate a possible mechanism of fibre hyperplasia. Giddings, Neaves and Gonyea (1985) suggest that satellite cells provide myogenic material for these new fibres and they are activated through the mechanical stress of training. The fact that sattelite cells are found in adult muscle and are involved in the muscle regeneration involved in myopathies (Muir 1970) which offers support for this hypothesis. Salleo et al. (1980) observed the enlargement of satellite cells, their separation from the "parent cell" and the subsequent formation of elongated structures from these cells, similar to myogenesis, during compensatory hypertrophy in the rat plantaris. Goldberg (1975) noted the occurrence of lateral budding of fibres in overloaded rat muscle and proposed it as a method of hyperplasia. MacDougall et al. (1982) have hypothesized a "ceiling size" for fibres beyond which, optimal functioning is impossible due to increased diffusion distances.

Although fibre hyperplasia may occur in muscle exposed to resistance training over a prolonged period, its contribution to gains in muscle size observed with strength training is probably minimal and non-significant.

I. Involuntary Contractile Properties

The response of involuntary contractile properties to muscle hypertrophy has been studied for a number of reasons. In human studies, involuntary twitch and tetanically stimulated tension have been used to attempt to differentiate changes in the tension development capabilities of the muscle with the "neural adaptations" which have been shown to affect increases in strength. In animal studies, these measurements of tension have demonstrated the functional significance of hypertrophy in compensatory hypertrophy or resistance training studies. Contraction and relaxation times and rate of torque development indicate the intrinsic, time-related contractile characteristics of the muscle. Interest in these properties arises from the observed relationship between contraction and relaxation times and fibre type (Buchtal and Schmalbruch, 1970) and the possibility of altering fibre type or other muscle properties involved in time-related contractile properties (e.g. calcium kinetics) with exercise. Anecdotally, coaches have often said that strength training can "slow you down", giving possible practical implications for this work.

1. Human Studies

Cross-sectional and longitudinal studies have been done on strength training and involuntary contractile properties in human muscle.

Twitch tension has been shown to increase with isometric training of the adductor pollicis (Duchateau and Hainaut, 1984) and isometric and weight training in the hypothenar muscle (Liberson and Asa, 1959) of the hand. Other studies have shown no increase in twitch force with isometric training in the triceps surae (Davies and Young, 1981; Davies and McGrath, 1982) and elbow flexors (McDonagh, Hayward and Davies, 1983). Duchateau and Hainaut (1984) observed a significant decrease in twitch torque with fast, ballistic training. Sale et al. (1983) observed greater twitch torque in the triceps surae of trained male body builders versus control subjects, however Alway (1985) observed no difference in twitch torque between these two groups in the same muscle group. Due to the chronic use of the triceps surae in daily activity, this muscle group may not be best to use in cross-sectional studies such as these. Greater twitch torque has also been observed in the elbow flexors of body builders (Tsunoda, O'Hagan and Sale, 1985).

Tetanic tension increases of 11 and 21% have been observed following 13 weeks of ballistic and isometric training of the adductor pollicis muscles (Duchateau and Hainaut, 1984). Tetanic stimulation is quite painful and therefore has not been used in many human studies. However, it is probably a more sensitive indicator of changes in the intrinsic capabilities of the muscle than twitch torque as it allows for the "taking up" of elastic elements within the muscle and full activation of the "active state" of the muscle which could confound twitch tension measurements.

Decreases in contraction and relaxation times have been observed with ballistic, but not isometric training of the adductor pollicis muscle (Duchateau and Hainaut, 1984). These changes were accompanied by increases in maximum rate of torque development and relaxation with isometric and ballistic training. No effect on contraction time has been observed with isometric training of the elbow flexors (McDonagh, Hayward and Davies, 1983) or triceps surae (Davies and McGrath, 1982) however twitch contraction time has been shown to change differentially in the elbow flexors of body builders versus untrained control subjects with changes in elbow position (O'Hagan, Tsunoda and Sale, 1986). Isometric training has been shown to decrease twitch contraction time in the triceps surae (Alway, 1986) and thenar muscles of the hand (Sale et al., 1982) however increased twitch time has been observed in the triceps surae of trained male body builders compared with untrained controls (Sale et al., 1983) and trained endurance athletes (Alway, 1985). The reason for these apparent discrepancies may be the type of training engaged in by bodybuilders (dynamic) compared with the isometric training of the longitudinal studies.

2. Animal Studies

Several studies have examined the effect of resistance training on the contractile properties of animal muscle. Tetanic tension has been shown to increase with isometric training (Exner et al., 1973a,b), dynamic resistance training (Edgerton, 1976; Gonyea and Bonde-Petersen, 1978) and loaded running (Stone and Lipner, 1978). Increases in twitch torque were observed by Gonyea and Bonde-Petersen (1978) and Stone and Lipner (1978).

Increases in twitch contraction and 1/2 relaxation times were observed by Gonyea and Bonde-Petersen (1978) while Exner et al. (1973b) observed increase in twitch time to peak torque in the soleus with a significant decrease in rectus femoris of isometrically trained rats. Edgerton (1976) and Stone and Lipner (1978) observed no changes in time related contractile characteristics. Intense swimming exercise has been shown to decrease twitch time to peak torque (Gutmann and Hajek, 1971).

Compensatory hypertrophy has been used extensively to study changes in muscle contractile properties with muscle hypertrophy. Tetanic tension has been shown to increase (Binkhorst, 1969; Jewel and Zamais, 1954; Freeman and Luff, 1982; Binkhorst and van't Hof,1973; Walshe et al., 1982; Goldberg et al. 1975; Rowe, 1969; Roy et al., 1982) as well as twitch tension (Binkhorst, 1969; Jewel and Zamais, 1954; Roy et al., 1982; Goldberg et al., 1975) in muscle undergoing compensatory hypertrophy. Some of these studies have observed decreases in the twitch to tetanic tension ratio (Roy et al., 1982; Rowe, 1969; Walshe et al., 1982; Binkhorst and van't Hof, 1973) and this has been attributed to changes in the elastic component or active state of the muscle (Binkhorst and van't Hof, 1973).

Increases in twitch time to peak torque have been observed in "slow" (Vrbova, 1963; Guttman, Schiaffino, and Hanzlikova, 1971; Goldberg et al., 1975; Rowe, 1969) and "fast twitch" muscle (Vrbova, 1963; Gutmann, Hajek and Horsky, 1969; Gutmann, Hajek and Vitek, 1970; Gutmann and Hajek, 1971; Gutmann, Schiaffino and Hanzlikova, 1971; Roy et al., 1982; Goldberg et al., 1975) following compensatory hypertrophy. Binkhorst and van't Hof (1973) observed decreases in maximum shortening velocity in muscles undergoing compensatory hypertrophy and ascribed this effect to an increase in angle of pinnation of fibres.

Gutmann and Hajek (1971) advised caution in interpreting time-related contractile property results obtained from the compensatory hypertrophy model. These authors observed opposite effects between the compensatory hypertrophy model (increased twitch time) and "excessive use" swimming exercise (decreased twitch time) on the rat extensor digitorum longus muscle. In addition to this, the changes in muscle protein that are observed with compensatory hypertrophy are quite different from that observed with training, as increases in contractile protein are predominant with resistance training but increases in sarcoplasmic protein are greater with compensatory hypertrophy (Gutman and Hajek, 1971). These authors suggested that the two models are mutually exclusive. It should be noted however, that the differential effects observed in this model are in agreement with the findings of Duchateau and Hainaut (1984) in humans, if we assume that the compensatory hypertrophy model is an example of isometric loading and the swimming training as analogous to ballistic training.

3. Summary

Short-term studies in human muscle have not shown any effect on involuntary contractile properties (e.g. McDonagh, Hayward and Davies, 1983) however extended training would seem to increase the tetanic (Duchateau and Hainaut, 1984) and twitch (Duchateau and

Hainaut, 1984; Sale et al., 1983) tension capabilities. The decrease in twitch tension observed with ballistic training by Duchateau and Hainaut (1984) was probably due to the nature of that training and may be due to changes in muscle elasticity as suggested by Binkhorst and van't Hof (1973) or alterations in sarcoplasmic reticulum, affecting the muscle's active state. The training studies in animals would seem to agree with these findings (eg. Gonyea and Bonde-Petersen, 1978).

Extreme strength training would seem to increase twitch time to peak tension and half relaxation time if we take the most representative studies as being those of Sale et al. (1983) in humans and Gonyea and Bonde-Petersen (1978) in animals. The mechanism of this adaptation is unclear. Alway (1985) found no alteration in sarcoplasmic reticulum volume density with either strength training or in a chronically strength trained group, suggesting something other than ultrastructure to account for these changes. Although the results in compensatory hypertrophy studies suggest increases in time to peak torque and 1/2 relaxation timmes, this model is not representative of the excessive use involved with strength training.

J. Conclusion

In summary, strength training results in adaptations which increase the strength of the muscle, in part through hypertrophy of the muscle. Increases in muscle size are a result of hypertrophy of existing fibres. It is unlikely that fibre hyperplasia contributes significantly to increases in muscle size. Strength training may also result in an enhancement of involuntary tension producing capabilities (by increasing contractile protein) and a "slowing" of the contraction time of the muscle as reflected by increased time to peak twitch tension and twitch half relaxation times, the mechanism of which has yet to be elucidated.

Chapter III

Methods

A. Subjects

6 male (21 ± 1.2 y) and 6 female (20 ± .8 y) physical education students served as subjects. No prior intense strength training had been performed by the subjects and all other heavy resistance exercise was proscribed throughout the training program. Informed consent of the subjects was obtained with approval of the study by the McMaster University Research Ethics Committee. Height (cm) and pre and post training mass (kg) were recorded and are given in Table 1-A.

B. Design

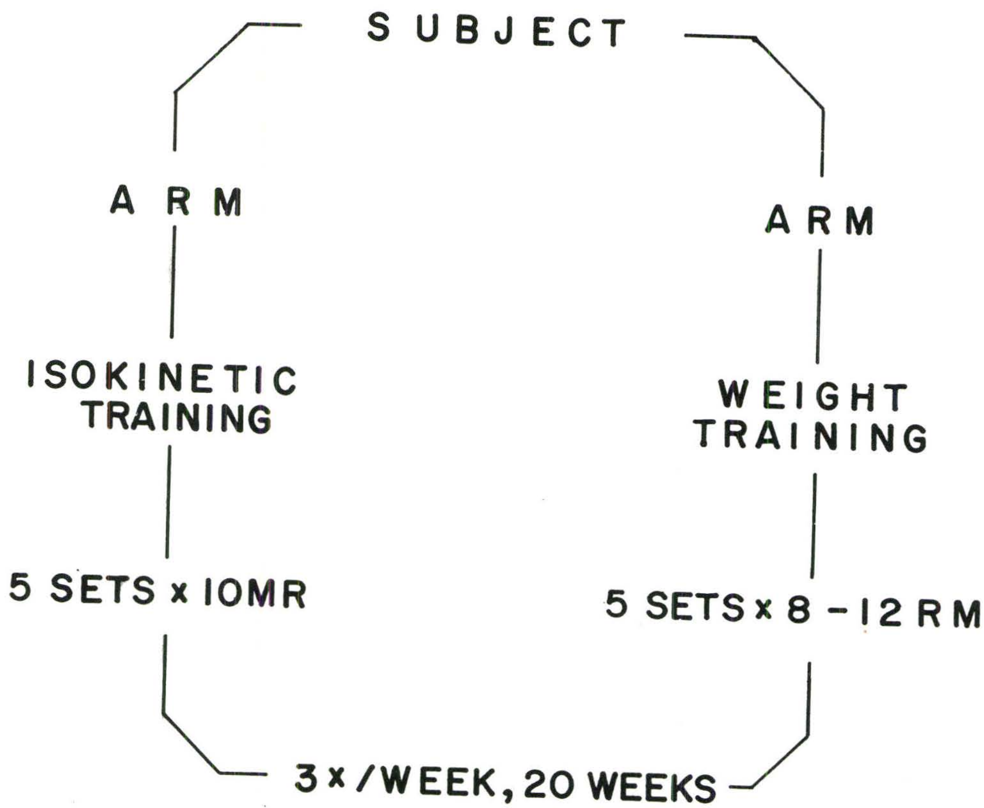
Training programs were randomly assigned such that 6 subjects (3 males, 3 females) trained their dominant arms using the isokinetic device and their non-dominant arm using the weight device. The other 6 subjects trained the dominant arm on the weight device and the non-dominant arm on the isokinetic device. This design allowed each subject to serve as his or her own control enabling an examination of the merits of the two forms of training within each subject (Figure 1-A).

Table 1-A

Subject Descriptive Data

	Age (years)	Height (cm)	Weight (kg) Pre	Weight (kg) Post
Males	21.0 ± 1.2	176.2 ± 3.2	74.6 ± 3.7	74.2 ± 3.5
Females	20.0 ± .8	165.4 ± 4.4	57.6 ± 3.1	60.2 ± 3.0

Figure 1-A. Schematic drawing of the experimental design. Each subject trained one arm on the isokinetic device and one on the weight device, thus serving as his or her own control.


SUBJECT
ARM
ISOKINETIC TRAINING
5 SETS x 10MR
ARM
WEIGHT TRAINING
5 SETS x 8 - 12 RM
3 x /WEEK, 20 WEEKS

C. Apparatus

1. Isokinetic Device

Isokinetic training took place on a hydraulic resistance device (Hydra-Gym Inc., Belton, Texas). The resistance on this device was provided by a hydraulic cylinder which functions by forcing fluid through an adjustable aperture. The equipment is not truly isokinetic as some acceleration of the arm was possible and the actual velocity depended on the strength of the subject; however, it is the form of isokinetic training most commonly used by athletes and does accommodate resistance through the range of motion. True isokinetic loading systems (e.g. Cybex, Kin/Com) are seldom available to athletes for training. The hydraulic cylinders of the training device were equipped with force transducers, enabling peak force measurements to be made. A schematic diagram of this device is given in Figure 1-B.

a. Validation of Isokinetic Properties

Quantification of angular velocity on this device was performed on 5 male subjects. A goniometer was strapped to the right arm and aligned with the lateral portion of the radius and humerus with the point of rotation about the lateral epicondyle of the humerus. Contractions were made at the training velocity (setting 6 on the device) and 2 faster test velocities (settings 3 and 1, the former being slower than the latter) and force as well as elbow displacement were measured on a chart recorder at a paper speed of 50 mm/s for the training velocity and 125 mm/s for the 2 faster velocities. Instantaneous velocity was determined at 0.1 s intervals

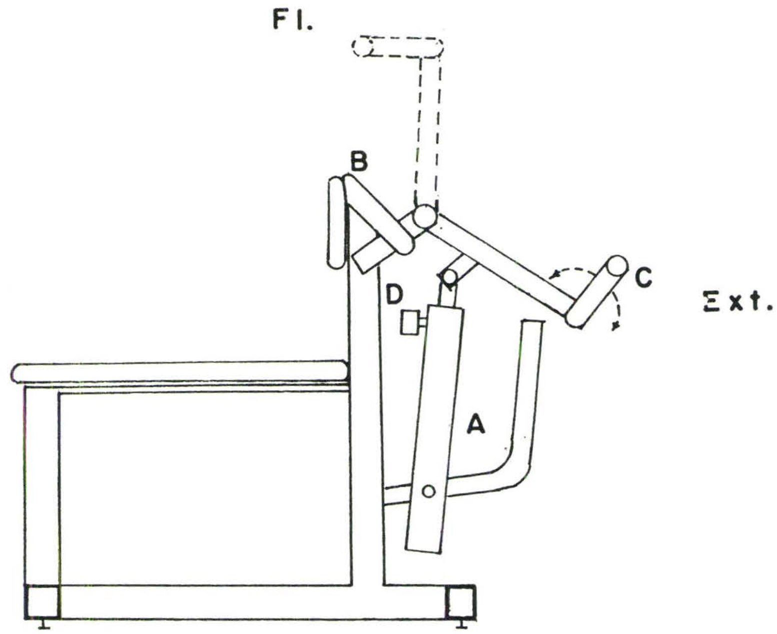
Figure 1-B. Schematic drawing of the isokinetic device in the flexed (Fl.) and extended (Ext.) positions.

A. Hydraulic cylinder used to provide resistance.

B. Pad on which the upper arm was supported during contractions.

C. Swivel handle to accomodate different arm lengths.

D. Force transducer through which the force measurements were made.


Fl.
B
C
D
A
Ext.

through the contractions.

The analysis revealed that there was an initial acceleration phase in contractions at the training velocity followed by an "isokinetic" phase for the remainder of the contraction (Figure 1-C). The acceleration phase accounted for approximately the first 20° of the contraction with the "isokinetic" phase accounting for the remainder. Angular velocity during the "isokinetic" phase varied from 35.2 to 51 °/s in the 5 subjects with a significant correlation between the force of contraction and the angular velocity during this phase (r=.89). A greater amount of variability was observed during the contractions at the 2 faster velocities (Figure 1-D) with average angular velocities of 146.6 °/s and 188 °/s observed at settings 3 and 1, respectively.

2. Weight Device

The custom-made weight resistance device (Rubicon Ind., Stoney Creek, Ont.) was designed such that the upper body and arm position matched that of the hydraulic device (Figure 1-E). Resistance was controlled through a stack of 10, 2.0 kg plates lifted through a one to one pulley system. Handle design and body position also matched that of the hydraulic device. Handles were constructed such that they extended from the end of the lever arm of the device and could swivel to accomodate different forearm lengths. The greatest resistance on this device was offered when the weight cable was perpendicular to the rotating shaft as the greatest resultant force by the weight stack would be in this position. This corresponded to a joint position of approximately 100° flexion (180° = full extension).

Figure 1-C. Representative tracing of force (A), elbow displacement (C) and and angular velocity (B) during a contraction at the training velocity on the isokinetic device. Figures A and C are traced from the original chart record An initial acceleration phase (as depicted by the peak on the velocity curve) was noted followed by an "isokinetic" phase for the duration of the contraction. See text for details.

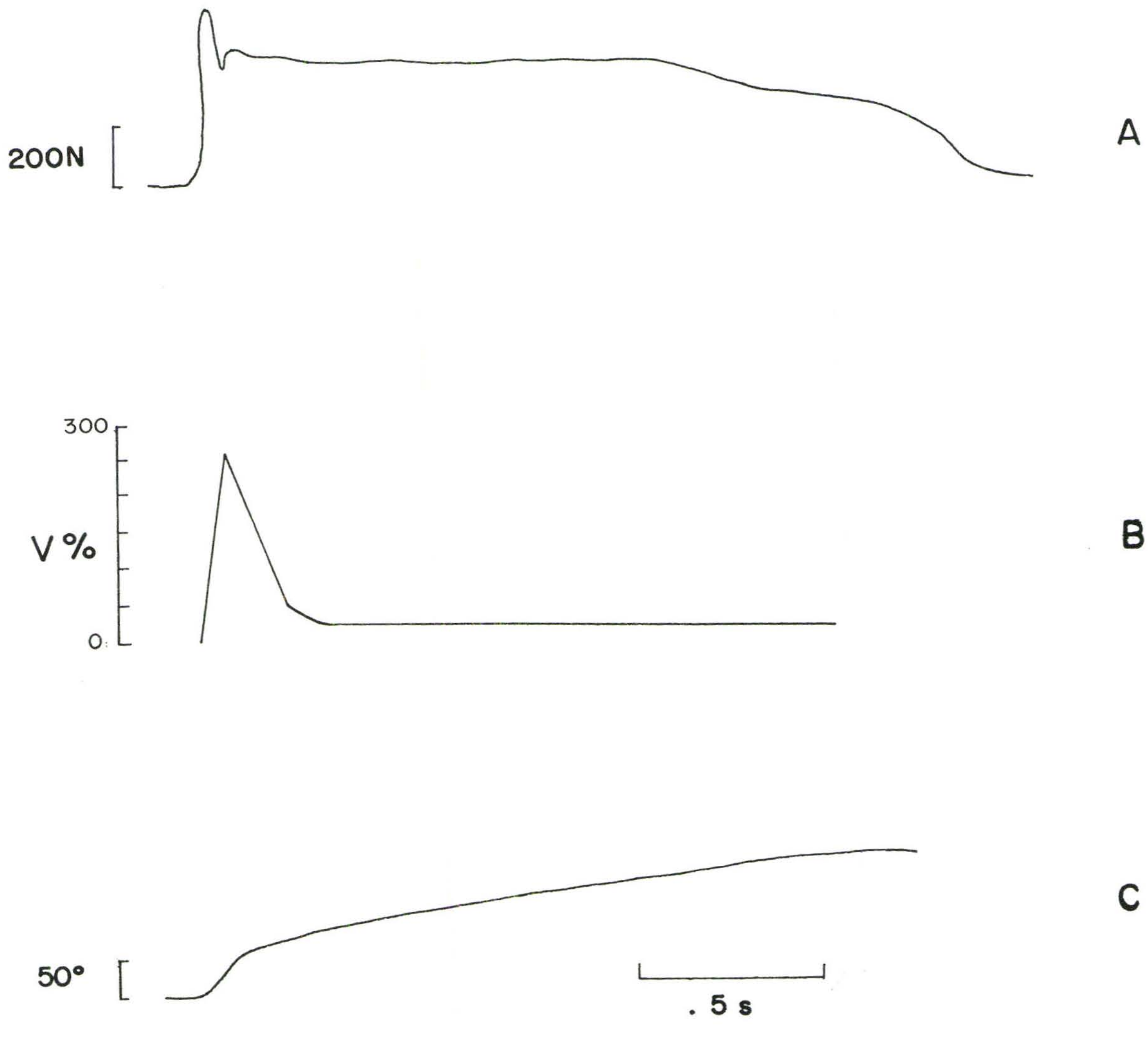

200N
A
300
V %
0
B
50°
. 5 s
C

Figure 1-D. Representative tracing of force (A), elbow displacement (C) and angular velocity (B) during a contraction at setting 3. Figures A and C are tracings of the original chart recording. See text for details.

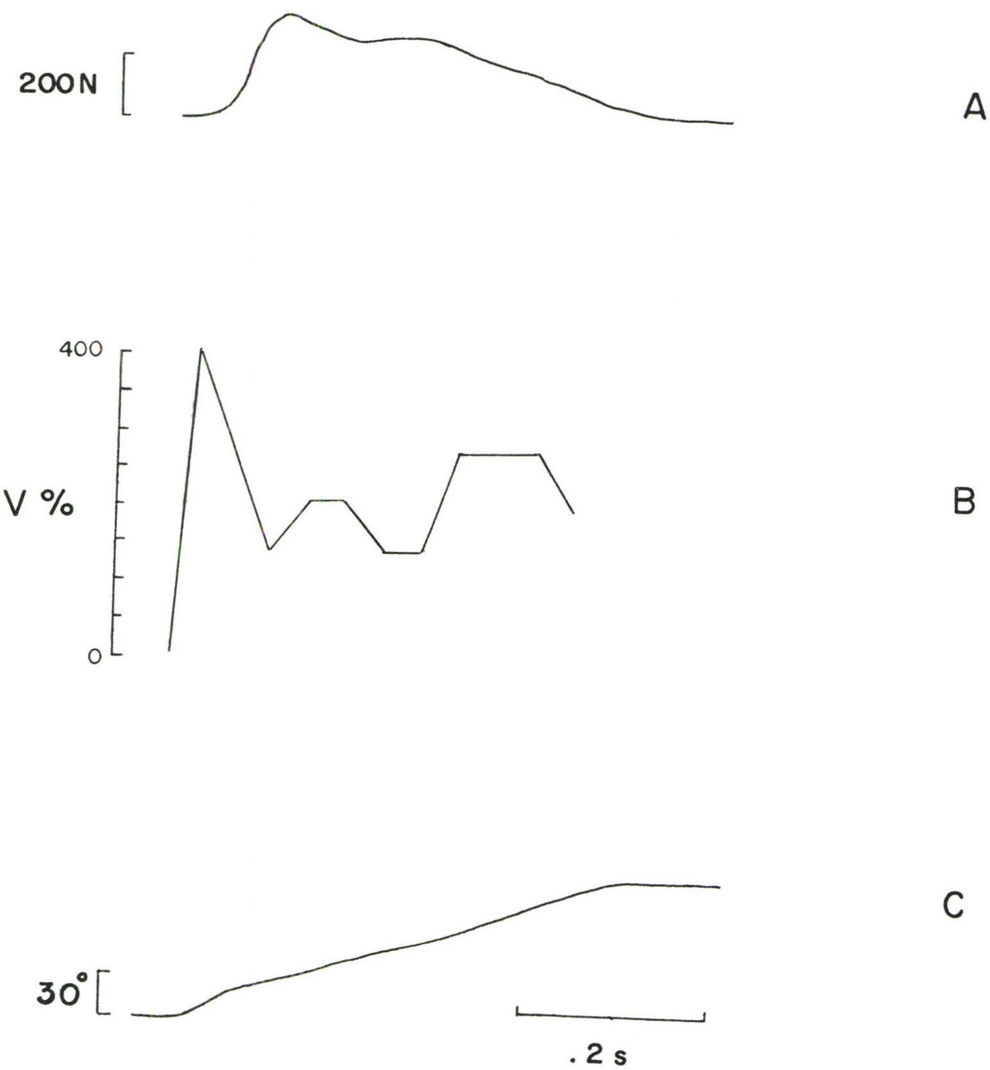

200N
A
400
V %
0
B
C
30°
.2 s

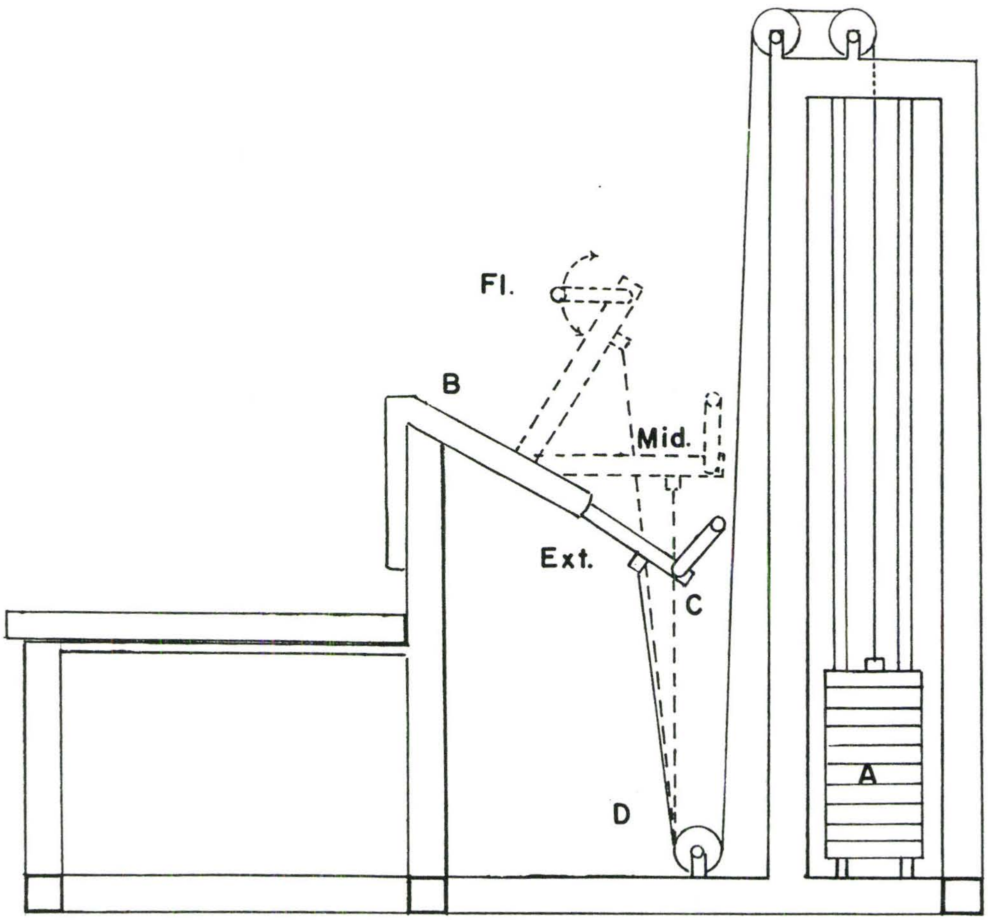
Figure 1-E. Schematic drawing of the weight training device.

A. Weight stack.

B. Support pad for upper arm.

C. Swivel handle for different arm lengths.

D. Cable from the weight stack to the arm.


Fl.
B
Mid.
Ext.
C
A
D

On both devices, subjects were seated in an upright position with the upper arm supported at approximately a 45° angle in a "preacher" type arrangement. Subjects were instructed to align the axis of rotation of the elbow with that of the lever arm for both training and testing.

D. Training

Subjects trained the elbow flexors of both arms 3 times per week for 20 weeks. Initially subjects performed one warm-up set and three sets of 8-12 RM on the weight device and 3 sets of 10 maximal repetitions on the hydraulic device. After 2 weeks, 4 training sets were performed with a 5th set added after 4 weeks. One warm-up set and 5 training sets were performed throughout the remainder of the training period.

The slowest speed ($\bar{X}$, 39.9 °/s) was utilized on the isokinetic device allowing for the greatest tension development over 10 maximal repetitions. Sets on the weight device were performed with a resistance allowing 8-12 repetitions to be done. A metronome was utilized to keep the speed of contraction on the weight device as close as possible to that of the hydraulic device.

Subjects worked alternately on the hydraulic device and weight device with a 1 min rest interval between sets; therefore, there was approximately 3 min of rest between sets for each arm.

An attempt to equate the amount of work done on each of the training devices was made by having the same number of contractions per training session performed on each device. Although the weight device necessitated an eccentric phase of contraction, the initial repetitions in a set of exercise on this device would be submaximal, owing to the fact that 10 repetitions had to be performed in each set. As well as this, maximal contractions are performed from the outset of exercise on the isokinetic device so the absolute amount of work done on each was considered approximately equal. In a practical sense, the training protocol used in this study would be representative of common training methods on both devices.

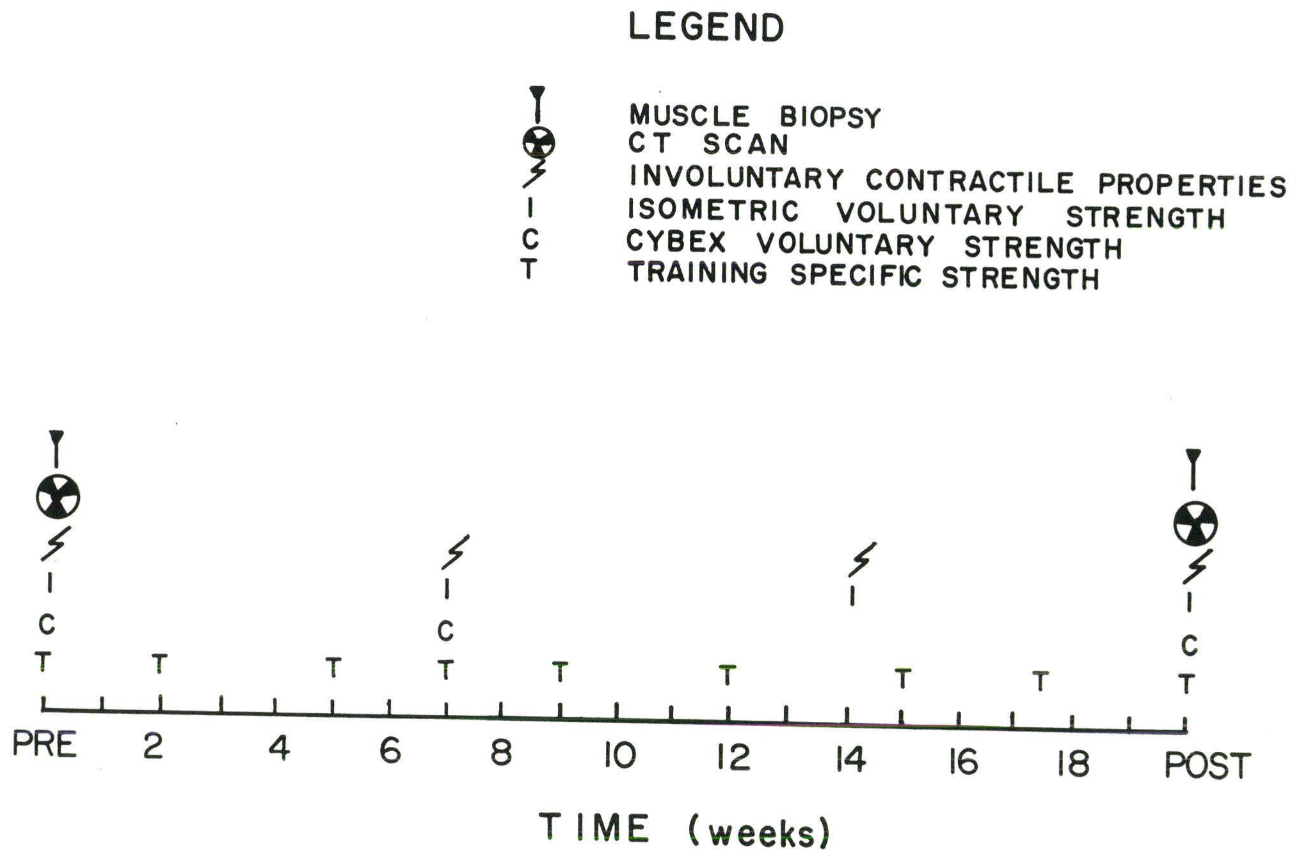
E. Dependent Measures

The time course of the dependent measures is depicted in Figure 1-F.

1. Maximum Strength Measurements

Both the isokinetic and weight trained arm were tested for 1 repetition maximum (1RM) strength on the weight device (WD) and peak force output (MVC) on the isokinetic device (ID) at slow (6), medium (3) and fast (1) speeds. These tests were performed at 2 to 3 week intervals throughout the study. One-repetition maximum (1RM) strength values were determined on the weight device by progressively increasing the load lifted, beginning at approximately 60% of the estimated 1RM value, until failure occurred. Upon failure, the load was dropped to one greater than the last successful attempt and adjusted until the 1RM value was found (within .25 kg). The load was increased in 1 kg increments for the females and 2 kg increments for the males. The test order of velocities was randomized on the ID. Three to 4 trials were given at each velocity, with the greatest of these taken as the MVC value.

Figure 1-F. Time course of the dependent measures during the training interval.


LEGEND
MUSCLE BIOPSY
CT SCAN
INVOLUNTARY CONTRACTILE PROPERTIES
I ISOMETRIC VOLUNTARY STRENGTH
C CYBEX VOLUNTARY STRENGTH
T TRAINING SPECIFIC STRENGTH
PRE
2
4
6
8
10
12
14
16
18
POST
TIME (weeks)

In order to quantify non-specific strength (ie. strength tasks relatively unfamiliar to either training mode), subjects were also tested for peak torque output on the Cybex dynamometer in random order at speeds of 30, 120, 180, and 240 °/s and for isometric peak torque at joint angles of 75, 90, 105, 120, 135, 150 and 165° elbow flexion on a custom-made dynamometer (see electrophysiology measurements below). Cybex measurements were made before training, after 7 weeks of training and post training. Isometric measurements were made before training, after 7 and 14 weeks of training and post training. Two warm-up contractions were given with 4 maximum strength trials (or until torque levelled off) at each velocity. The best of these trials was taken as the maximum strength value. A 15 s rest interval was given between trials. Joint angle order was randomized on the isometric device. A 2-3 s maximum voluntary contraction (MVC) was performed (or until torque levelled off) at each angle with a 1 min rest interval between contractions.

2. Muscle Area Measurements

Biceps, total flexor cross-sectional and humerus cross-sectional areas (cm^2) were measured from computerized tomography (CT) scanning (Model 20-30, Ohio Nuclear) pre and post training. Scans were taken of the upper arm, in an extended position, at a level 40% of the distance from the radio-humeral articulation to the coracoid process. Slide photographs of the scan image were taken and projected on to a flat surface and then traced on to paper with biceps, brachialis and humerus areas distinguished. Areas from these tracings were determined through planimetry using a computerized digitizing platform (Compucolor Inc.) and a custom-made software program. During these measurements, the investigator was unaware as to which training mode was used on the musculature being analysed.

3. Fibre Area Measurements

Needle biopsy tissue samples were obtained from the biceps brachii pre and post training. Muscle tissue samples were oriented under a dissecting microscope, embedded in Tissue Tek OCT embedding medium and frozen in isopentane, cooled to near its own freezing point in liquid point in liquid N2. Tissue was stored in a freezer at -50º C until analysis. Ten um thick sections were cut from the samples and mounted on glass slides. Fibre type was determined by the method of Padykula and Herman (1955) at a preincubation pH of 10.0. Type II fibres were labile in this condition.

Photomicrographic slides with non-overlapping fields were taken of a single cross-section of stained tissue at a microscope magnification of 10X on an Olympus BHA microscope with an Olympus photomicrograph camera (model PM-10-A). Fibre areas were determined through planimetry of fibres from projected slides on a computerized digitizing platform (Compucolor Inc.) using a custom-made software program. For each tissue sample, an average of 80 Type I and 100 Type II fibre areas were determined. Care was also taken to ensure that no longitudinally sectioned fibres were measured. Fibre area measurements were made with the investigator blind to the identity of the sample. Mean fibre areas were used for analysis and Type II:Type I fibre area ratios were calculated from these means.

4. Electrophysiology Measurements

Twitch contractions were measured on a custom-made dynamometer which allowed for measurements to be made at any joint angle in the range of motion.

The upper arm rested on a horizontal plate and the forearm was secured in the vertical plane with velcro straps to a second plate which could be rotated to change the elbow position. The shaft about which this plate rotated was equipped with a torque transducer consisting of strain gauges. During measurements, this shaft was secured creating an isometric condition. The torque signal from the transducer was amplified by a custom-made amplifier and converted by an A-D converter to a digital signal. The amplified signal was fed to a storage oscilloscope (Hewlett-Packard Inc.) for viewing and the digital signal was fed to a PDP-03 computer (Digital Equipment Corp., Maynard, Mass.) for analysis. A custom-made software package enabled torque (N.m), time to peak torque (ms), 1/2 relaxation time (ms) and maximum rates of torque development and relaxation (N.m/s) to be measured.

Maximal, isometric twitch contractions of the elbow flexors were evoked through percutaneous stimulation. Large lead plate electrodes (3X4 cm) were placed over the belly of the biceps and the forearm flexor compartment. Electrodes were covered with gauze impregnated with conductance cream and soaked with water, before being secured to the arm with surgical tape and wrapped with elastic bandages. Fifty µs square wave impulses (Digitimer Stimulator model 3072) were delivered with increasing voltage intensity until no further increase in twitch torque was observed on a storage oscilloscope (Hewlett-Packard model 1201B). This was taken to be the maximum twitch response. A single trial was then given and recorded. This procedure was repeated following each change in joint angle as it was observed that the stimulus intensity required to elicit a maximal twitch contraction varied with joint angle. Voltage intensity ranged from 200 - 400 volts. Because of the size and positioning of the stimulating electrodes, measurement of M waves was not possible. Therefore, it was assumed that full activation of the muscle was achieved when twitch torque failed to increase with further increases in stimulus intensity.

Twitch contractions were evoked in random order at joint angles of 75, 90, 105, 120, 135, 150 and 165 degrees elbow flexion (180° = full extension). Twitch contractions were always performed prior to isometric MVC measurements (see strength measurement above) to avoid potentiation effects. These measurements were made pre, at 7 weeks and 14 weeks and post training.

5. Statistical Analyses

Stastical analyses were performed with analysis of variance for a mixed design with 1 between group factor. A Tukey A post hoc test was used for post hoc analysis. Level of significance was set at $p<.05$.

Chapter IV

Results and Discussion

The results and discussion are divided into 2 sections; the first discusses the differences found between modes of training and differential effects observed between training modes according to gender; the second discusses the differences in response between males and females to identical training programs. Data are presented collapsed across gender in the first section and training mode in the second, with combined means and SE for males and females or isokinetic and weight conditions given. Significance was set at $p<.05$ for post hoc analysis unless otherwise stated. Numerical values for the data are tabled in Appendix A and B.

A. Isokinetic vs Weight Trained Conditions

1. Results

The following section is concerned with differences found between training modes across the training period as well as gender by mode by time interactions. Main effect differences between training mode are given, in which case, the data may be collapsed across velocity of contraction in the Cybex or isokinetic measurements. In the case of interactions between training mode and gender, MI will denote the male isokinetically trained condition, MW the male weight trained condition, FI the female isokinetically trained condition and FW the female weight trained condition.

a. Strength Performance Measurements

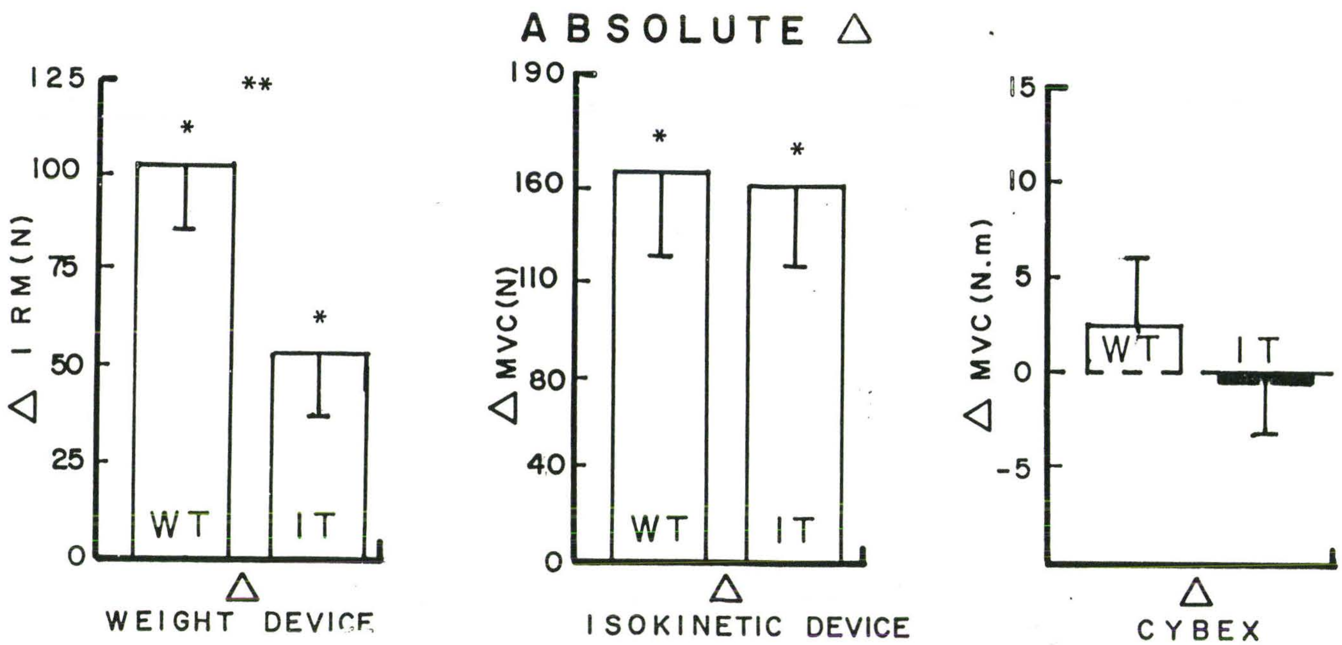
i. Absolute Strength

Training specific strength measurements were made on both training apparatus, as well as non-specific strength measurements taken on a Cybex at 4 velocities and on an isometric dynamometer at 7 joint angles. Changes in absolute strength measured on the training devices and the Cybex are summarized in Figure 1-1; results from the isometric dynamometer are given in Figure 1-4.

Strength measurements were made on the training apparatus at 2-3 week intervals throughout the training period. On both the weight device and isokinetic device, strength increased in a linear manner in the isokinetic and weight trained conditions. An example of this is given in Figure 1-2 which shows 1 RM weight device values in both conditions from pre to post training. No evidence of a "plateau effect" was noted in either condition on training specific strength measurements.

No overall difference in Cybex peak torque changes was observed between modes of training at any point during the training period. However, the interaction observed between training mode, gender and velocity revealed that the MW, 30 °/s value improved significantly (+6.17 N.m) with no change observed in the MI condition (Fig. 1-3). No difference in increases were observed between training

Figure 1-1. Absolute changes in strength on the training devices and Cybex, pre to post training in the weight (WT) and isokinetically (IT) trained conditions. Data are collapsed across velocity for the Cybex and isokinetic device.
* Significant increase from pretraining, $p<.05$.
** WT significantly greater than IT, $p<.05$.
Values are $\bar{X} \pm$ SE.



ABSOLUTE Δ
125
100
75
50
25
0
Δ 1 RM (N)
*
**
*
WT
IT
Δ
WEIGHT DEVICE
190
160
110
80
40
0
Δ MVC (N)
*
*
WT
IT
Δ
ISOKINETIC DEVICE
15
10
5
0
-5
Δ MVC (N.m)
WT
IT
Δ
CYBEX

Figure 1-2. 1 RM force across the training period in weight and isokinetic conditions. A progressive, linear increase was observed from pre to post training in strength measured on both training devices.
** IT significantly greater than WT, $p<.05$.
* WT significantly greater than IT, $p<.05$.
Values are $\bar{X} \pm SE$.

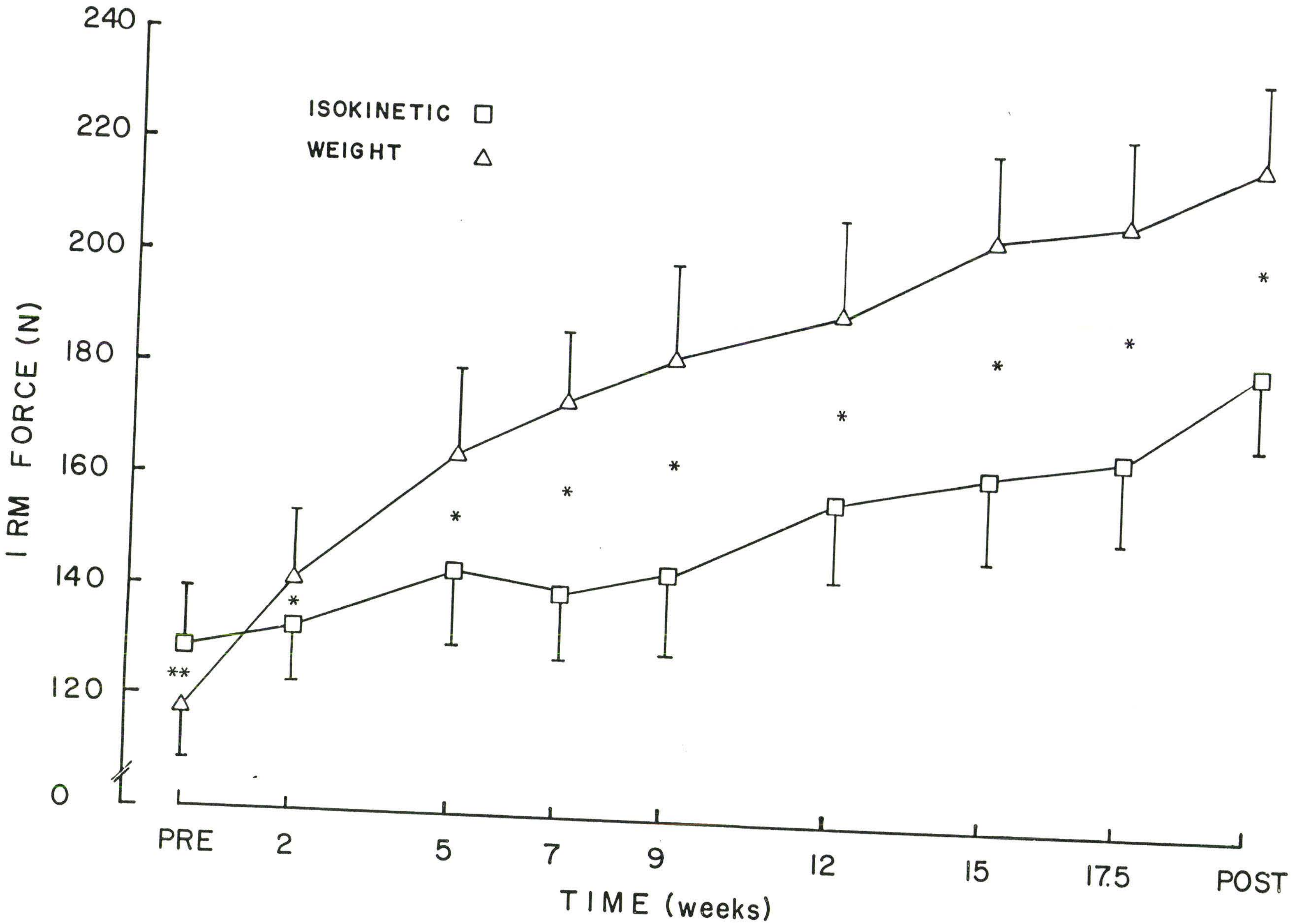
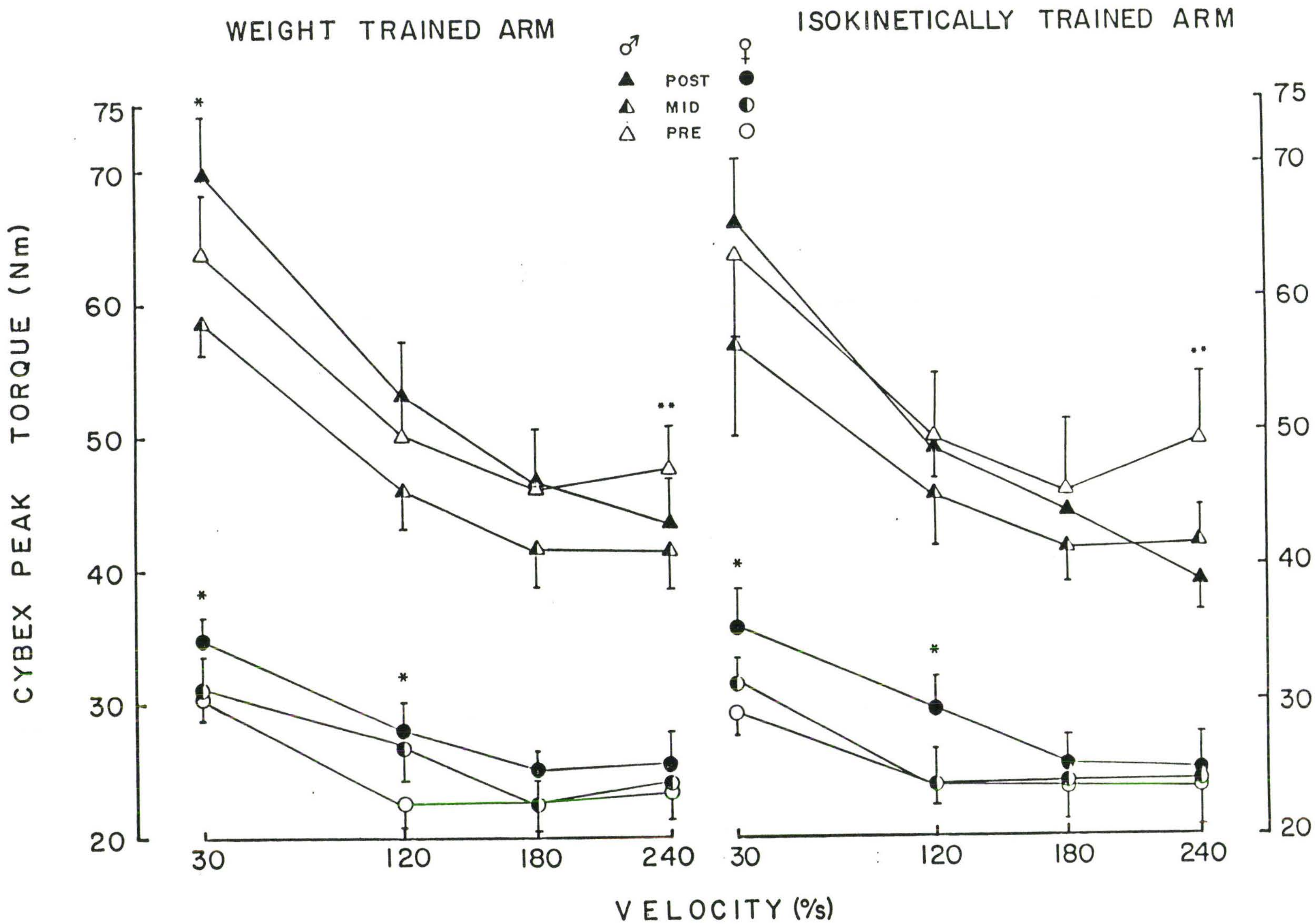

ISOKINETIC
WEIGHT
IRM FORCE (N)
240
220
200
180
160
140
120
0
PRE
2
5
7
9
12
15
17.5
POST
TIME (weeks)
**
*

Figure 1-3. Cybex peak torque pre, 7weeks and post training in male and female isokinetic and weight trained conditions.

* Significant increase from pretraining, $p<.05$.

** Significant decrease from pretraining, $p<.05$.

Values are $\bar{X} \pm SE$.


WEIGHT TRAINED ARM
ISOKINETICALLY TRAINED ARM
♂ ♀
POST
MID
PRE
CYBEX PEAK TORQUE (Nm)
VELOCITY (°/s)
75
70
60
50
40
30
20
30
120
180
240

devices in females.

No overall difference was observed between training modes in peak torque changes on the isometric dynamometer. The isokinetic condition, however, increased only at joint positions ranging from 75 to 105°, after which no difference was observed between pre and post training (Figure 1-4).

Absolute MVC values on the isokinetic device increased in both the weight and isokinetically trained conditions. Increases were greater at the slowest (training) velocity than the 2 faster test velocities. No overall difference was observed between training modes. There was, however, a significant mode by gender by time interaction which showed that the MI condition exceeded that of MW at the slowest contraction velocity at 17.5 weeks and post training (Figure 1-5).

The 1RM weight device values increased significantly with both isokinetic (58.6%) and weight (102.9%) training. 1 RM force in the weight trained arm was significantly lower than the isokinetically trained arm, pretraining. This situation was reversed by 2 weeks of training and force in the weight condition remained significantly greater than the isokinetic condition to post training (Figure 1-2).

ii. Relative Strength

Relative values for isometric peak torque, isokinetic MVC and weight 1RM were calculated and analysed as percentages of the pretest value. Due to the small changes observed in Cybex peak torque, it was omitted from this analysis. Values given in the text are % increases. Data are summarized in Figure 1-6.

No difference existed between training modes in relative

Figure 1-4. Isometric peak torque across joint angles, pre and post training in weight and isokinetic conditions. A significant increase in peak torque was observed from pre to post training ($p < .03$) with no difference between conditions. Values are $\bar{X} \pm SE$.

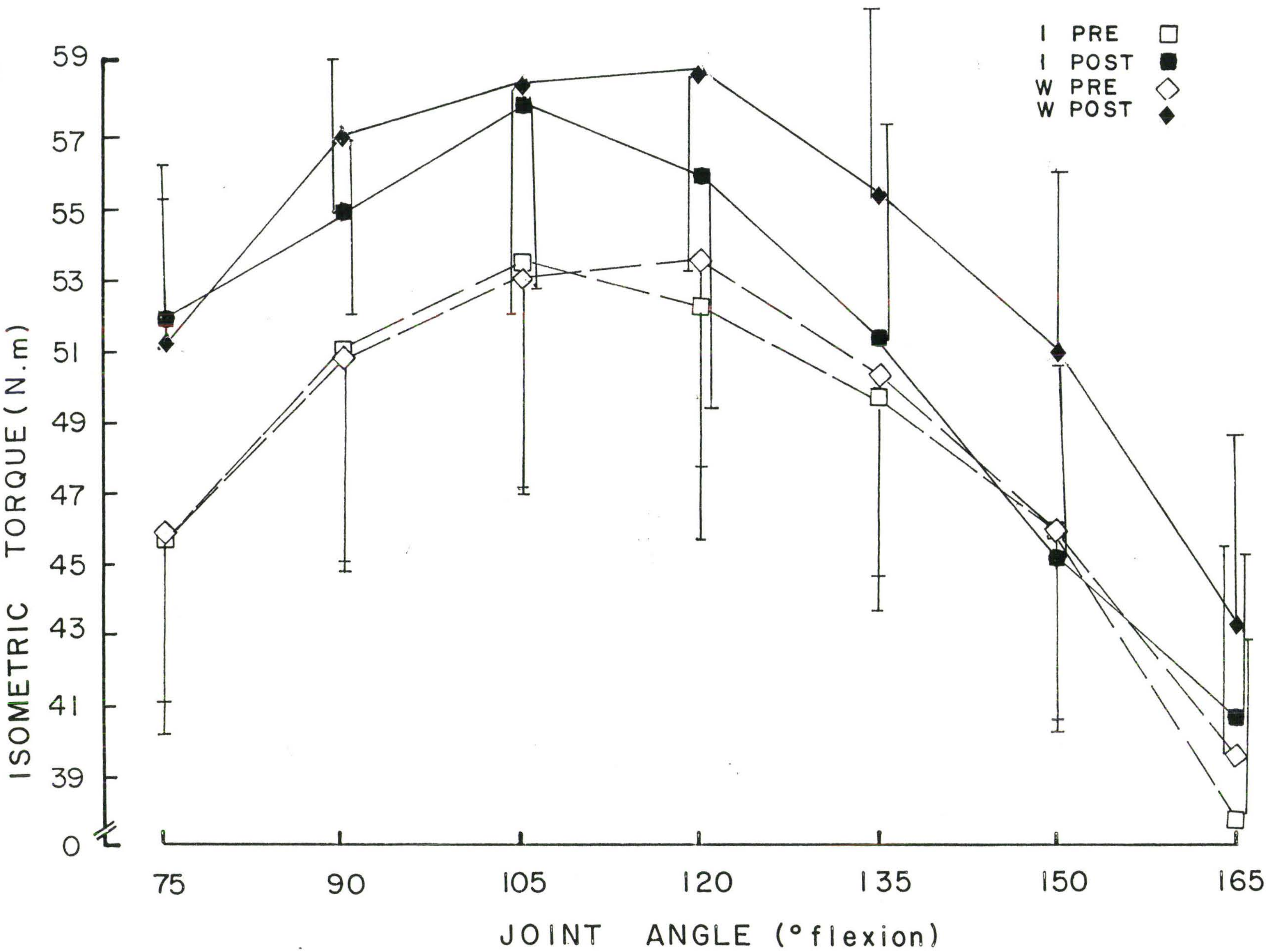

I PRE
I POST
W PRE
W POST
59
57
55
53
51
49
47
45
43
41
39
0
ISOMETRIC TORQUE (N.m)
75
90
105
120
135
150
165
JOINT ANGLE (° flexion)

Figure 1-5. Isokinetic force (N) across the training period in male isokinetic (IT) and weight (WT) conditions. Values are $\bar{X} \pm$ SE.

* IT significantly greater than WT, $p<.05$.

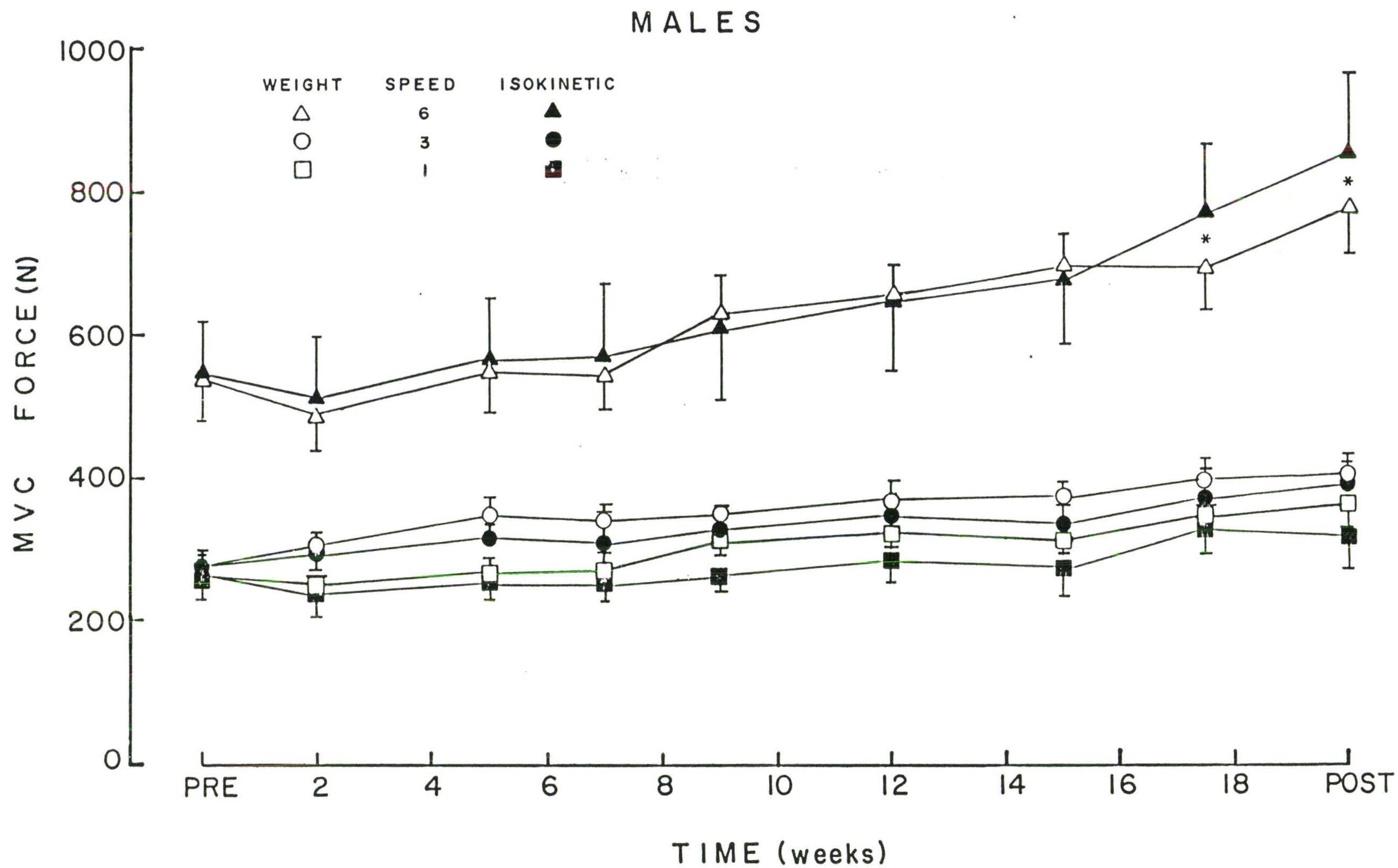
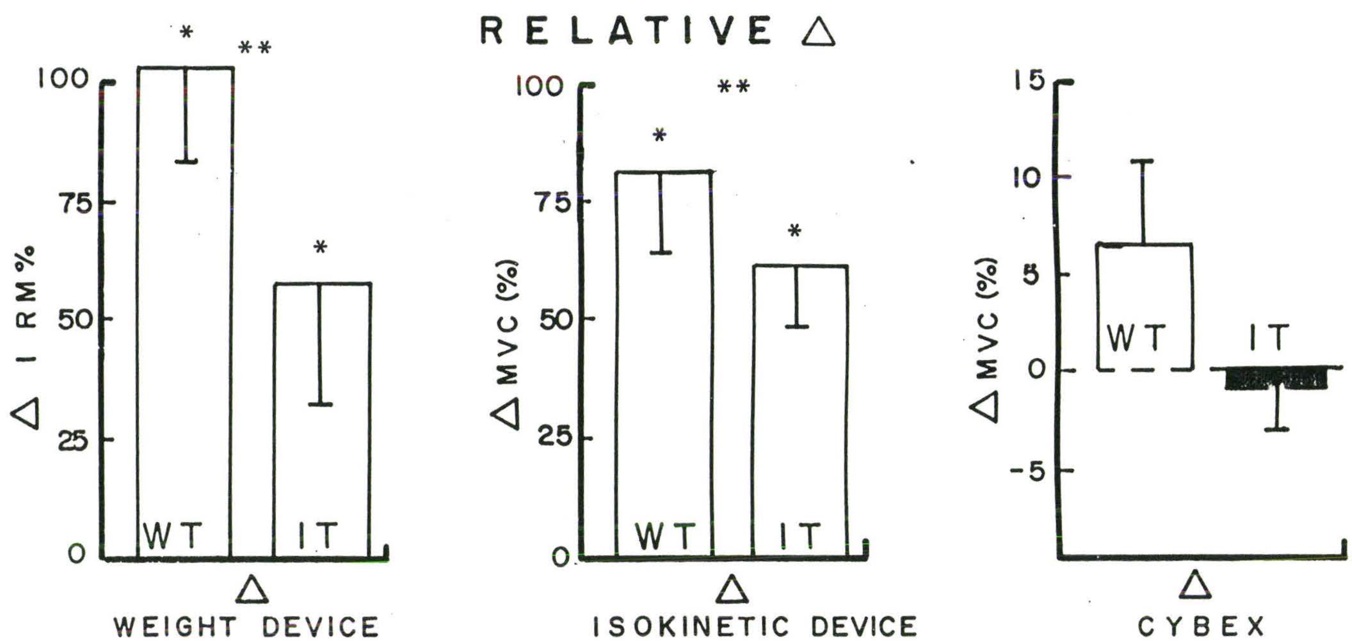

MALES
WEIGHT
SPEED
ISOKINETIC
6
3
1
MVC FORCE (N)
1000
800
600
400
200
0
PRE
2
4
6
8
10
12
14
16
18
POST
TIME (weeks)
*
*

Figure 1-6. Relative changes in strength on the training devices and Cybex in weight (WT) and isokinetic (IT) conditions. Data are collapsed across velocity for the Cybex and isokinetic device. Values are $\bar{X} \pm$ SE.

* Significant increase from pretraining, $p<.001$.

** WT significantly greater than IT, $p<.05$.


RELATIVE Δ
100
75
50
25
0
Δ 1 RM%
WT
IT
Δ
WEIGHT DEVICE
100
75
50
25
0
Δ MVC (%)
WT
IT
Δ
ISOKINETIC DEVICE
15
10
5
0
-5
Δ MVC (%)
WT
IT
Δ
CYBEX

isometric MVC increases.

In terms of relative strength increases on the isokinetic device, the weight trained condition had larger overall increases in MVC values than the isokinetically trained condition (81.8 vs 61.7%, Figure 1-6). This was evident from 2 weeks of training onward. The interaction found between mode, gender and velocity showed that by the post training measurement, FW had improved significantly more than FI at the two slowest velocities (141.5% vs 96.8% at 6, 119.6% vs 78.7% at 3, $p<.002$) while no differential effects were evident in the males (Figure 1-7).

Relative changes in the 1RM values (Figure 1-6) were greater in the weight trained condition than the isokinetically trained condition. The gender by mode by time interaction found revealed that the increases in FW exceeded that of FI from 5 weeks of training onward and MW from 2 weeks of training onward (Figure 1-8). MW and FI did not differ in their response throughout the training period.

b. Gross Muscle Morphology

Cross-sectional areas of biceps and brachialis were determined by CT scanning. Data were analysed in both absolute (cm^2) and relative (% pretest) terms (Figure 1-9).

Biceps cross-sectional area was significantly greater following training in both the isokinetic (1.06 cm^2) and weight conditions (.93 cm^2). Bicep area was significantly greater in the weight trained condition, pre and post training ($p<.004$), however no mode by time interaction was observed.

Brachialis area was significantly greater after training in

Figure 1-7. Relative isokinetic force (% pretest) in female isokinetic (IT) and weight (WT) conditions from pre to post training. * WT significantly greater than IT at that velocity, $p<.05$. Values are $\bar{X} \pm SE$.

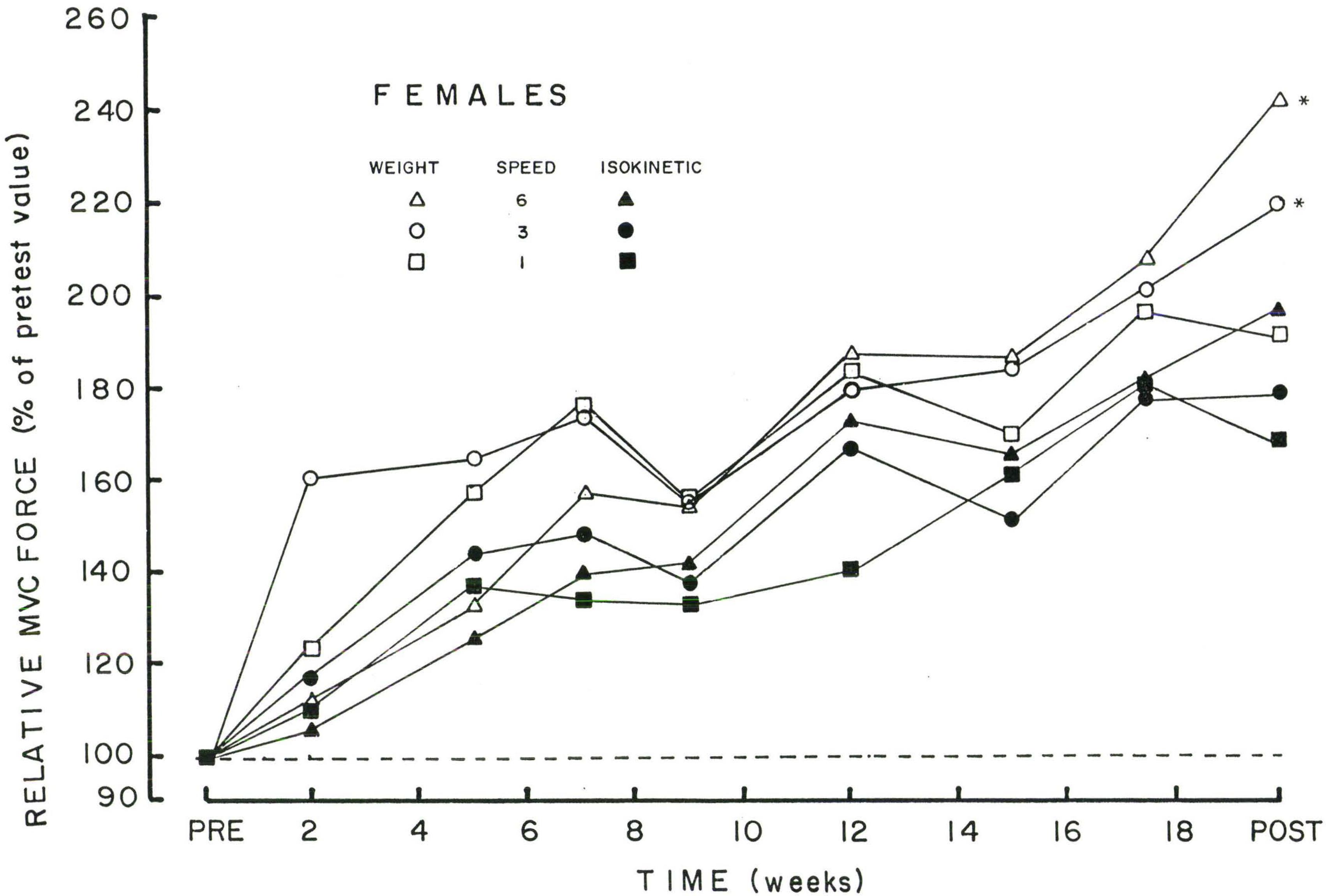

FEMALES
WEIGHT
SPEED
ISOKINETIC
6
3
1
RELATIVE MVC FORCE (% of pretest value)
260
240
220
200
180
160
140
120
100
90
PRE
2
4
6
8
10
12
14
16
18
POST
TIME (weeks)
*
*

Figure 1-8. Relative 1 RM values (% pretest) from pre to post training in male and female weight (WT) and isokinetic (IT) conditions.

* Female WT significantly greater than all other groups, $p<.05$.

** Female IT and male WT significantly greater than male IT, $p<.05$.

Values are $\bar{X} \pm SE$.

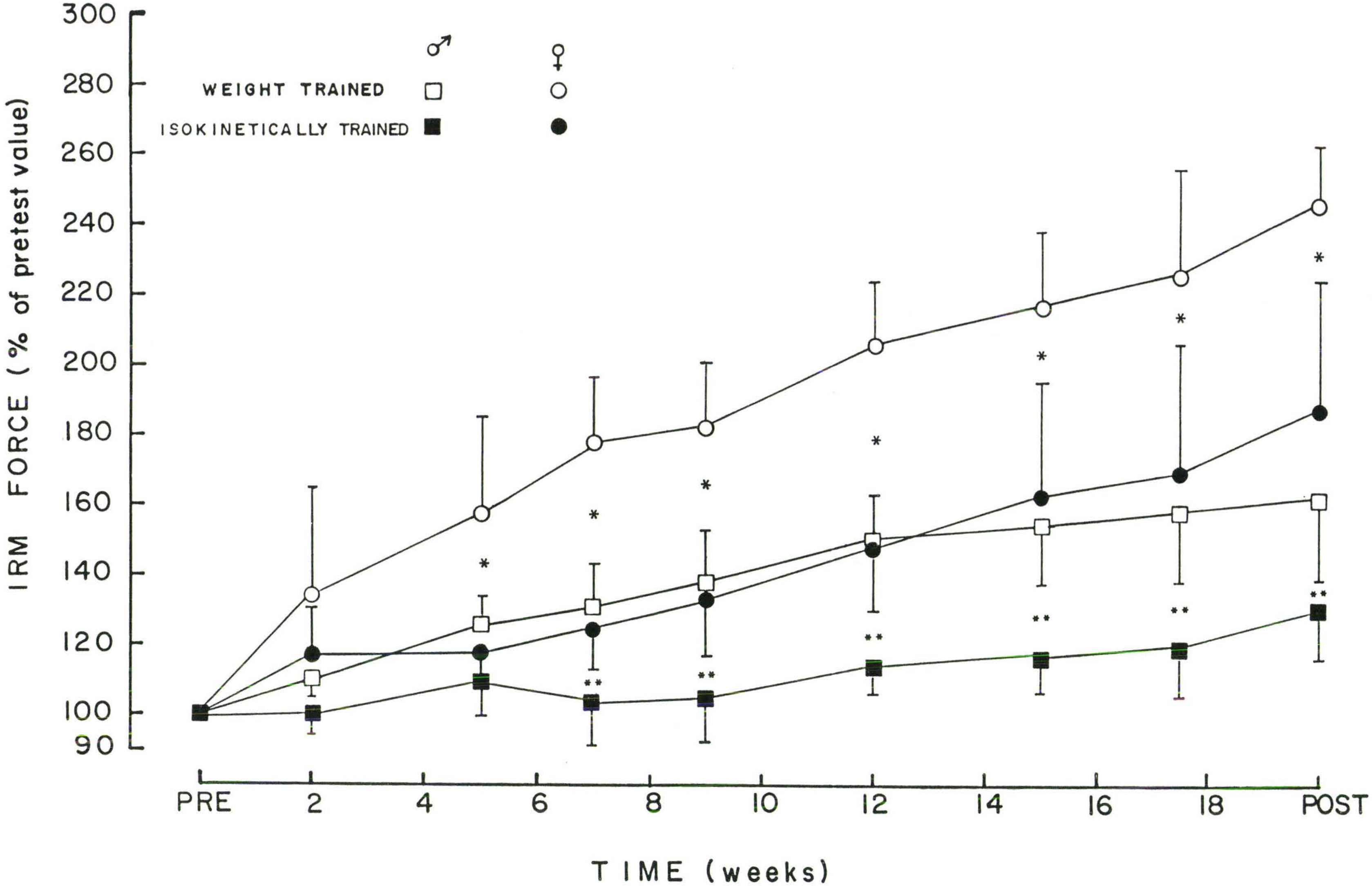
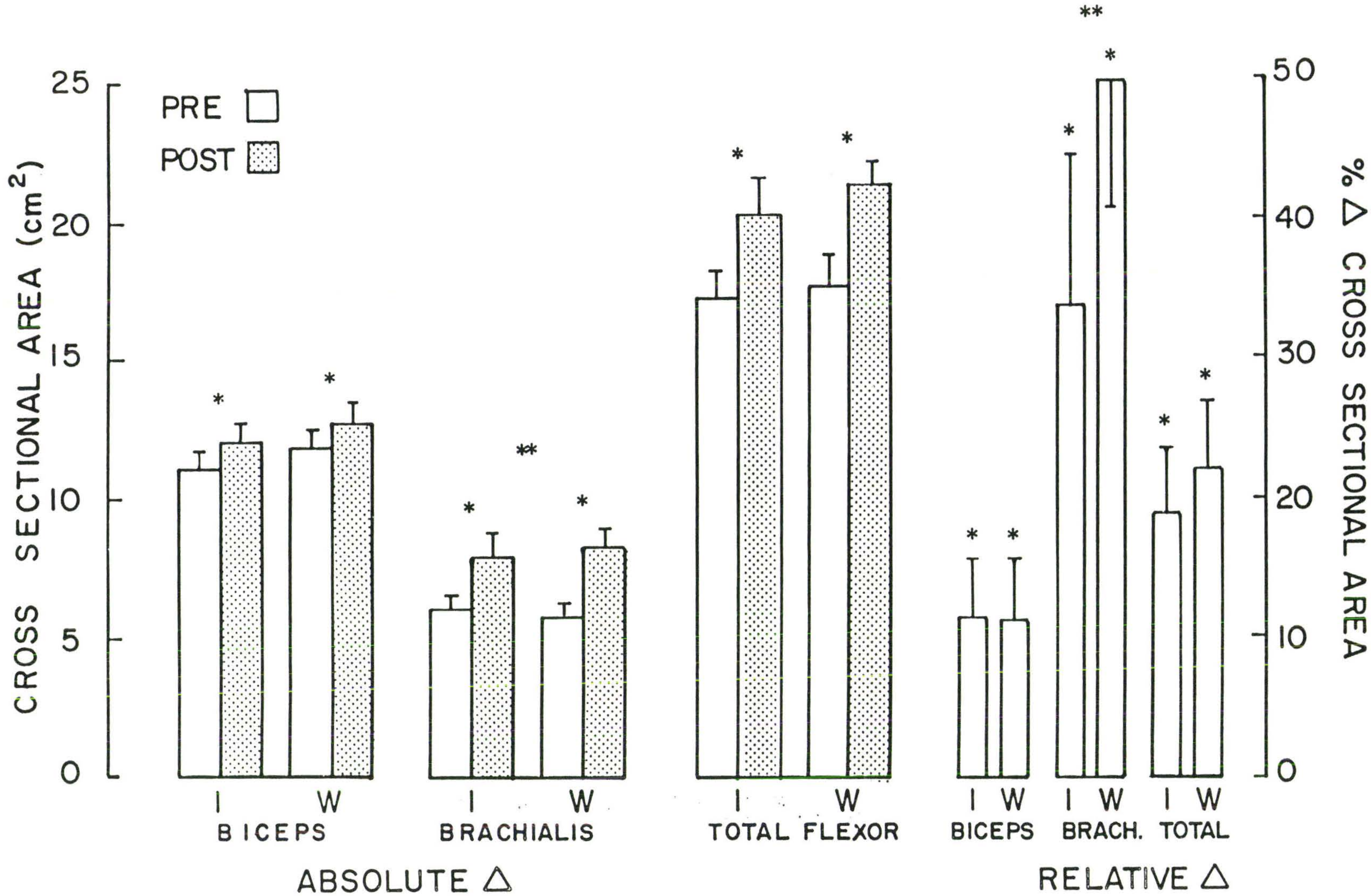

♂
♀
WEIGHT TRAINED
ISOKINETICALLY TRAINED
IRM FORCE (% of pretest value)
300
280
260
240
220
200
180
160
140
120
100
90
PRE
2
4
6
8
10
12
14
16
18
POST
TIME (weeks)

Figure 1-9. Changes in biceps, brachialis and total flexor cross-sectional areas in absolute and relative terms in weight (W) and isokinetic (I) conditions.

* Significant increase from pretraining, $p<.05$.

** W significantly greater than I, $p<.05$.

Values are $\bar{X} \pm SE$.


PRE
POST
CROSS SECTIONAL AREA (cm2)
0
5
10
15
20
25
% Δ CROSS SECTIONAL AREA
0
10
20
30
40
50
*
**
I
W
BICEPS
BRACHIALIS
TOTAL FLEXOR
BICEPS
BRACH.
TOTAL
ABSOLUTE Δ
RELATIVE Δ

both conditions ($p<.001$). Weight training produced a significantly greater increase in brachialis area (2.58 vs 1.86 cm^2).

Total flexor cross-sectional area increased significantly from pre (17.4 cm^2) to post (20.6 cm^2) training in all conditions. Values for the weight conditions were again significantly greater before and after training; however, no differential effects were observed between conditions.

In terms of relative changes, biceps area increased significantly over the training period with no difference between training modes (Figure 1-9). Relative increases in brachialis area were significant in both conditions with greater increases in the weight trained condition (25.0 vs 16.9%, $p<.01$).

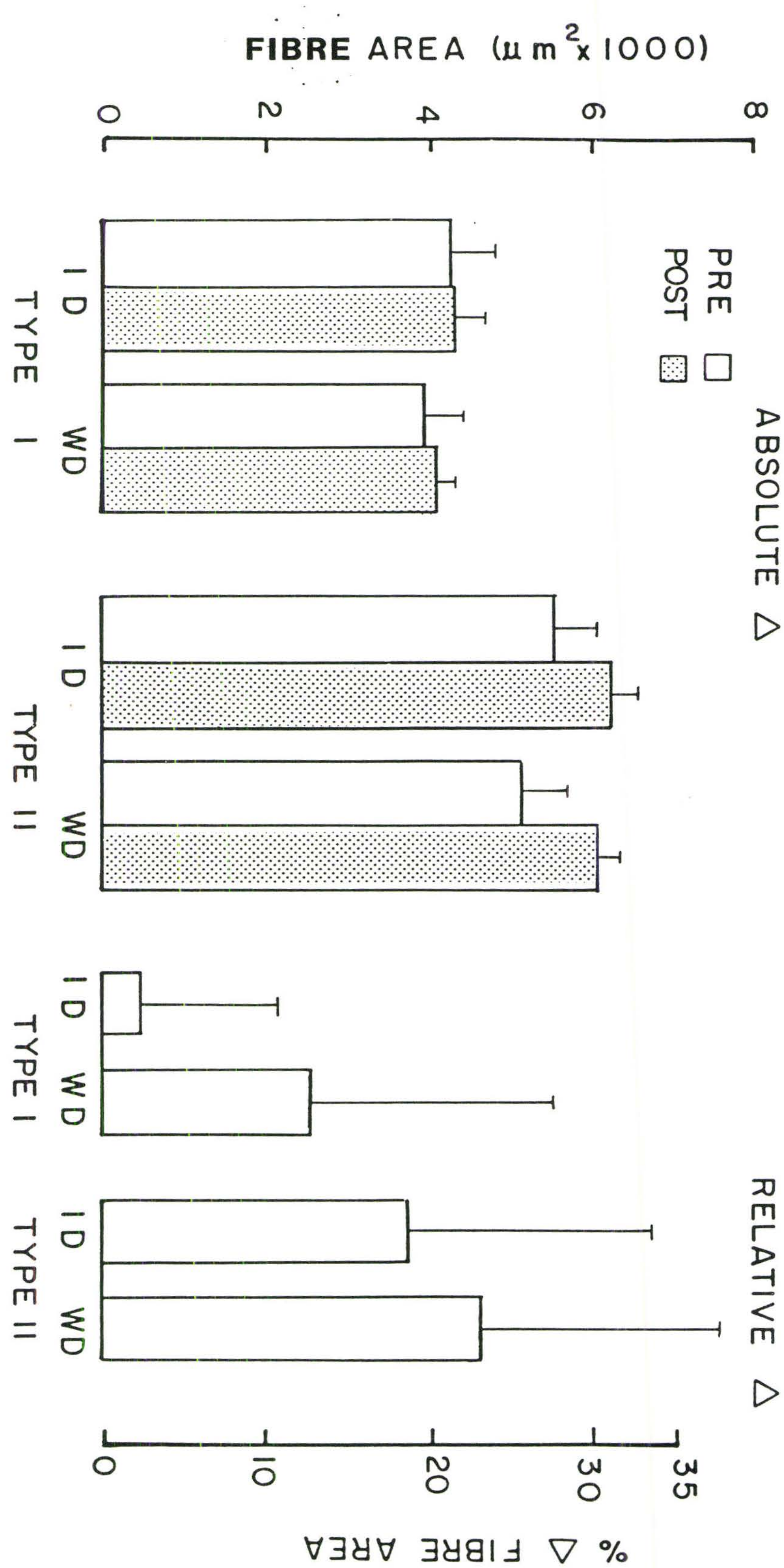
Relative changes in total flexor cross-sectional area were again significant in both conditions and no differential effect was observed between mode of training.

c. Fibre Areas

Absolute fibre areas (Figure 1-10) did not increase significantly following training ($p<.16$) although increases were observed in both the weight (542.5 μm^2) and isokinetic condition (345.5 μm^2). Although no main effect for training was observed, there was a definite trend ($p<.08$) for greater increases in the Type II fibres (+541.2 vs -90.4 μm^2).

When fibre areas were expressed as a percentage of the pretest value (Figure 1-10), the increases approached significance ($p<.07$). The weight trained condition increased by 17.9% and the isokinetic condition by 10.5% (data collapsed across fibre type).

Figure 1-10. Absolute and relative changes in Type I and Type II fibre areas. Values are $\bar{X} \pm$ SE.


FIBRE AREA (µm² x 1000)
0
2
4
6
8
PRE
POST
ABSOLUTE △
I D
WD
TYPE I
I D
WD
TYPE II
I D
WD
TYPE I
I D
WD
TYPE II
RELATIVE △
0
10
20
30
35
% △ FIBRE AREA

Type II: Type I fibre area ratios increased significantly from pre (1.31) to post (1.45) training (data collapsed across mode). No difference was observed between training modes.

d. Involuntary Contractile Property Measurements

Maximum twitch contractions were measured on an isometric dynamometer at joint angles ranging from 75 to 165°. Values for peak torque (PT), time to peak torque (TPT), 1/2 relaxation time (1/2 RT) and maximum rates of torque development (MRTD) and relaxation time (MRTR) were determined from the torque signal and analysed.

Twitch peak torque was analysed in both absolute (N.m) and relative (% pretest) terms. Absolute PT (Figure 1-11) increased significantly from pre (5.46 N.m) to 14 weeks training (6.52 N.m), after which it declined significantly post training (6.1 N.m). No difference between mode of training was observed. The interaction found between joint angle and time revealed that the greatest increases in torque at 14 weeks occurred at joint positions of greatest flexion (75°, 90°) and increases in torque were maintained to the greatest extent at these joint positions, post training.

Relative values for peak torque (Figure 1-12) were significantly greater at 14 weeks (37.2%) and post training (29.9%). No overall difference was observed between modes; however, again a significant interaction was found between mode, gender and time. MW increased significantly less than MI at 7 weeks (3.3 vs 27%) and FW at 14 weeks (23.1 vs 57.4%) and post training (19.7 vs 43.1%). MI and FW tended to show the greatest increases across all joint angles while the MW condition increased to the least extent ($p<.04$).

Figure 1-11. Absolute twitch peak torque across joint angles, pre, 7 weeks, 14 weeks and post training. Data are collapsed across training mode.

* 14 week value significantly greater than pretraining, $p<.05$.

** Post training value significantly greater than pretraining, $p<.05$. Values are $\bar{X}$.

SE bars are omitted for clarity.

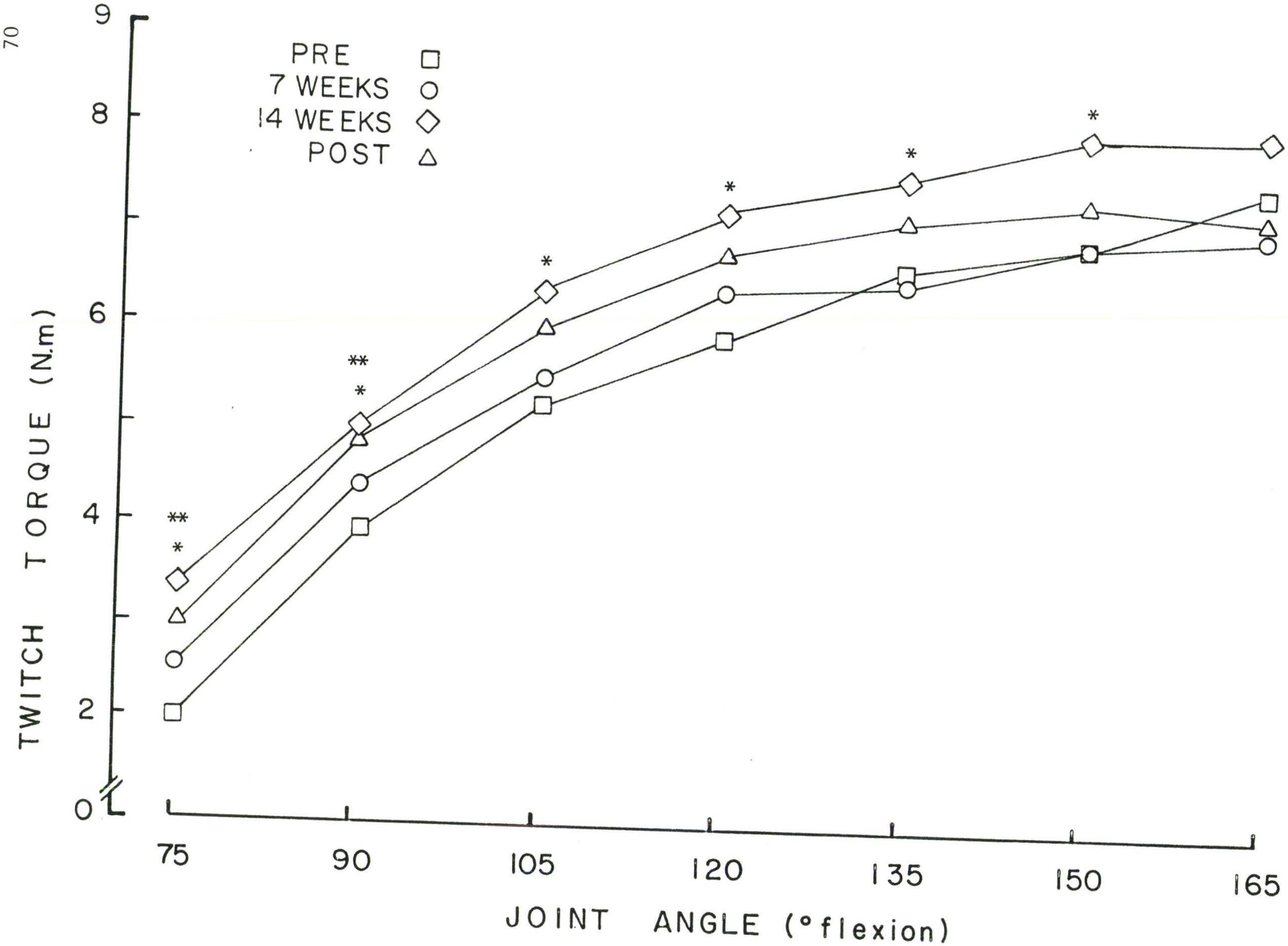
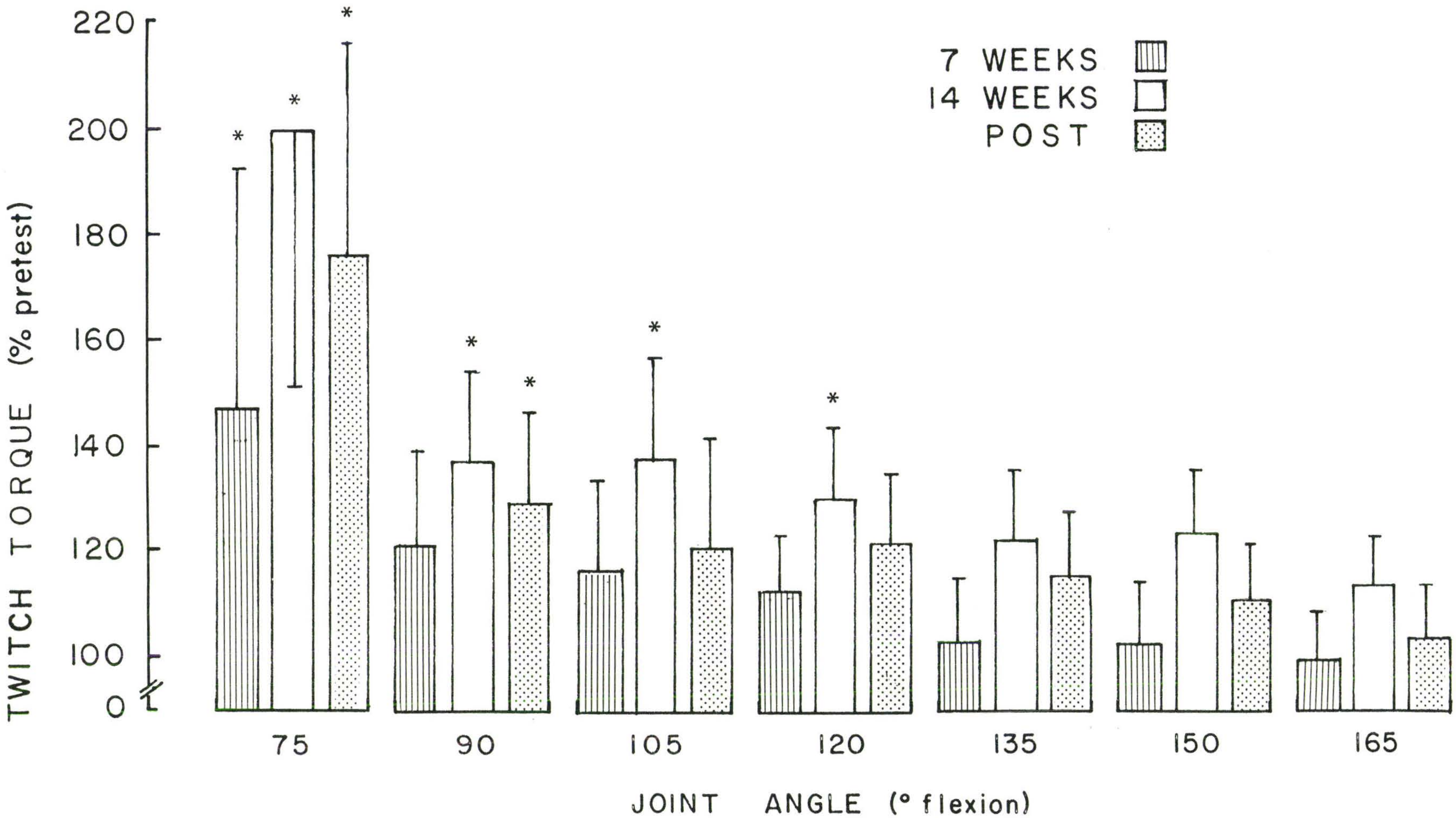

PRE
7 WEEKS
14 WEEKS
POST
TWITCH TORQUE (N.m)
JOINT ANGLE (°flexion)
0
2
4
6
8
9
75
90
105
120
135
150
165
**
*

Figure 1-12. Relative twitch peak torque across joint angles, pre, 7 weeks, 14 weeks and post training. Data are collapsed across training mode.

* Significant increase from pretraining, $p<.05$.

Values are $\bar{X} \pm SE$.


TWITCH TORQUE (% pretest)
220
200
180
160
140
120
100
0
7 WEEKS
14 WEEKS
POST
*
75
90
105
120
135
150
165
JOINT ANGLE (° flexion)

TPT values were little affected by training and no difference was observed between training modes at any point during the training period. An overall increase was observed in TPT at 75° from pre (58.2 ms) to post (66.3 ms) training. TPT showed a significant decrease across joint angles from 90°(63.3 ms) to 150° (58.3 ms).

1/2 RT was pimarily affected by joint position and to a lesser extent training. No difference was observed between training modes at any point during training. 1/2 RT decreased significantly following 14 weeks of training at 150°(93.1 to 74.8 ms) and 165° (85.7 to 75 ms) after which it returned to pre training values. 1/2 RT increased as the elbow was extended from 75 (59.9 ms) to 135° (85.6 ms) after which it remained unchanged to 165° (data collapsed across mode, time).

Alterations in MRTD and MRTR parralleled that of changes in peak torque. MRTD showed an overall increase as the elbow was extended. As occurred with PT, MRTD increased at 14 weeks of training after which it declined and was not significantly greater than the pre training value, post training. Only the isokinetic condition remained significantly elevated at 75, 105 and 120°.

MRTR increased significantly as the elbow was extended and, as with MRTD increased from pre training to 14 weeks after which it declined post training. MRTR increased in both conditions at 14 weeks at all joint angles. MRTR remained significantly elevated, post training, in the isokinetic condition at 75 and 90° and in the weight condition at 90, 105, 120 and 150°.

2. Discussion

The present study was unique from other training mode comparison studies in several respects. First, the duration of the study was considerably longer than previous work (eg. 4 weeks of training in Thistle et al. 1967). The author considers this to be important in the practical sense because most training and rehabilitation programs are longer than several weeks and in the scientific sense because it is known that in the initial 4 to 6 weeks of training little hypertrophy occurs (Moritani and de Vries, 1979). Secondly, this study employed more direct measures of muscle mass, using CT scans and muscle fibre areas which allow for much better resolution of the muscle's response to strength training. Lastly, specific as well as non-specific strength measurements were used, giving a more unbiased assessment of strength gains in the isokinetic and weight trained conditions. The remainder of the discussion will focus on differences found in the dependent measures between weight and isokinetically trained conditions.

a. Strength Performance Measurements

Strength gains made by both isokinetic and weight trained conditions were impressive when measured on both the isokinetic and weight device. Relative increases in weight device strength as a result of weight training were greater than that of a comparable previous study (MacDougall et al., 1977), however that study used only males as subjects and tested strength on an isokinetic dynamometer. There are no previous isokinetic studies with training periods as long as that of the present study; thus, it is hard to evaluate gains in isokinetic strength made with isokinetic training. Absolute isokinetic strength gains were quite similar in both training conditions; however, relative gains were greater in the weight trained condition. Absolute and relative strength increases measured on the weight device were greater in the weight trained arms.

Thistle et al. (1967) and Moffroid et al. (1969) both found greater increases in isokinetic strength in groups trained on an isokinetic compared to groups trained on a weight device. However, there is some question as to the equitability of work performed during training by the groups in these studies. In both of these studies the weight trained groups only performed 1 set of 10 repetitions with maximum resistance while the isokinetic groups performed 30 maximum repetitions on a Cybex. Although the weight trained group performed what might be considered the classical "Delorme method", with 2 submaximal sets of 10 repetitions followed by a single set of 10 RM, this method had already been demonstrated as being a less effective method of increasing strength than simply performing 3 sets of 10 RM (Hellebrandt and Houtz, 1956). This limits the interpretation of their results in terms of the training mode comparison as the greater gains in strength found with isokinetic training may have been due to the training protocol and not the devices used. Pipes and Wilmore (1975) did attempt to equate the work done between groups performing isokinetic and weight training and found greater increases in isokinetic strength with isokinetic training. Although no direct measurement of work was performed on the training devices in the present study, an attempt to equate work was done by using an equal number of repetitions on each training device (see methods).

The only study to measure strength performance on the weight training device was Pipes and Wilmore (1975) who found significant improvements in both weight trained and isokinetically trained groups with a high speed (136°/s) trained group showing the greatest increases. In the present study, the weight trained condition increased to a greater extent than the isokinetic condition in absolute and relative weight device strength. This may have been due to a specificity effect as well as the greater hypertrophy observed in the brachialis of weight trained arms (see below).

Increases in isometric dynamometer peak torque were relatively much smaller than gains made on the training devices and Cybex peak torque increased only minimally in both isokinetic and weight trained conditions. This is not surprising, however, as strength gains are specific to the mode of training as well as the velocity trained at (Sale and MacDougall, 1981). Although one might expect this also to be the case for the weight trained condition tested on the isokinetic device and vice versa, testing was carried out quite frequently (2-3 weeks), allowing for a substantial amount of familiarity between the training condition and its counterpart device. One might also have expected the isokinetically trained arms to perform better in strength measurements done on the Cybex; however, the body position in which the Cybex tests were performed was quite different from that of the training position on the isokinetic device and strength gains made with training are smaller when strength is tested at a position different from that of training (McMorris and Elkins, 1954; Rasch and Morehouse, 1957). Although there appears to be a significant interaction between training mode, joint angle and time in isometric dynamometer torque, such that the weight trained arm increased uniformly across joint angles while the isokinetic condition increased only at joint angles of greatest flexion, the variability was such that this effect was not significant.

In contrast to previous studies examining the efficacy of weight and isokinetic training, it would seem that when strength is tested on the devices which were used for training, greater strength gains were made with weight training. The reason for this apparent superiority may be due to the eccentric phase of contraction in this training providing additional stimulus for strength gain. Eccentric loading induces greater tension per active motor unit (Bigland-Ritchie and Woods, 1976) which may give weight training the advantage in strength improvement. It may also be due to the greater increase in brachialis area observed in the weight trained arms (see below). Differential effects in non-specific strength gains on the Cybex or isometric dynamometer were minimal, although the greater increase in Cybex torque in MW over MI at 30 /s may indicate more general strength gains for this training condition, at least in the males.

b. Muscle Cross-Sectional Area

No other study of this nature has utilized CT scanning to measure changes in muscle cross-sectional area. Thistle et al. (1967) and Moffroid et al. (1969) did not take anthropometric measurements in their comparative studies; however, no change would be expected over the relatively short, 4 week training period used in these studies. Pipes and Wilmore (1975) carried out girth measurements at the shoulders, chest and upper arm (extended and flexed). Both isokinetic and weight training increased girths significantly. Girth measurements are limited by the fact that they are affected by changes in subcutaneous fat as well as not being able to evaluate hypertrophy in specific muscle groups and, therefore, probably do not accurately assess muscle hypertrophy or are not sensitive enough to detect the small changes that may differentiate training modes. CT scans in the present study revealed increases in biceps, brachialis and total flexor cross-sectional area (absolute and relative). Although increases in brachialis area favoured the weight trained conditions in both absolute and relative terms, no differential effect was observed in the total flexor cross-sectional area. This was due to the added variability caused by combining biceps and brachialis areas for analysis. It would seem that both modes of training are effective in inducing hypertrophy in the elbow flexors. The greater increases in strength in the weight condition may be related to the larger increase in brachialis cross-sectional area if this muscle is the prime mover in this training.

An interesting finding was the greater increase in brachialis area (41%) compared to biceps area (9.9%). It is commonly assumed that although the brachialis is the prime mover for elbow flexion when the forearm is in a pronated position, both biceps and brachialis act to flex the arm when the forearm is placed in a position of supination as was the case during training in the present study (An et al., 1977; Hasan and Enoka, 1985). It is possible that the position imposed by the training devices ("preacher arrangement") as well as the lack of active supination (isometric or dynamic) loaded the brachialis to a greater extent than the biceps and therefore caused greater hypertyrophy in this muscle. It may be that the contribution to elbow flexion strength of the brachialis in this training position was greater than either of the 2 heads of biceps due to the fact that strength is dependent on the cross-sectional area of the muscle and the brachialis has a greater cross-sectional area than either bicep head (An et al., 1977). If the activity of the long head of the biceps was reduced due to the training position, and was no longer required to stabilize the shoulder with the upper arm supported as it was, the tension development of the brachialis would have been greater during the training, accounting for the greater hypertrophy response.

c. Fibre Area Measurements

Increases in fibre area have been observed in some studies using weight (MacDougall et al. 1980) and isokinetic (Coyle et al. 1980) training. Others have found no change in fibre area with weight (Thorstensson et al., 1976) or isokinetic (Costill et al., 1979) training. No muscle biopsy data have previously been analysed in a study comparing the 2 training devices. The apparent lack of increase in fibre size in the present study may be due to intra-subject variabilty in biopsy sampling. Numerous studies have shown variability in fibre areas calculated from successive biopsy samples taken from the same area of the muscle (Thorstensson et al. 1977, Haggmark, Jansson and Svane, 1978, Edstrom and Ekblom, 1972) which could confound the results of studies calculating fibre areas from single biopsy samples. As well as this, a recent study has shown increases in muscle area (using CT scan measurements) with no change in fibre areas following 7 weeks of strength training (Luthi et al., 1986). Also, since the biopsy sample was taken from the biceps, and the greatest hypertrophy was observed in the brachialis, fibre hypertrophy in the former may have been too small to detect, given the variability in biopsy sampling. The increase in Type II: Type I fibre area ratios following training supports previous cross-sectional (MacDougall et al., 1984, Schantz et al., 1983) and longitudinal (Thorstensson et al., 1976; Hakkinen, Alen and Komi, 1985, Houston et al., 1983; MacDougall et al., 1980) studies and supports the assertion that fibre hypertrophy caused by strength training occurs in both fibre types but to a greater extent in the Type II fibres.

d. Involuntary Contractile Properties

Few studies have assessed the effect of strength training on the involuntary contractile characteristics of human muscle. The present study found significant increases in twitch peak torque at 14 weeks of training but these increases were maintained only at certain joint positions following 20 weeks of training. The reason for the observed increase may be ascribed to the increase in muscle mass. Duchateau and Hainaut (1984) found significant increases in twitch torque with 13 weeks of isometric training and Sale et al. (1983) observed greater twitch torque in hypertrophied triceps surae of bodybuilders.

The decrease in twitch peak torque at 20 versus 14 weeks of training at most joint angles is harder to explain. The decrease could have been caused by systematic alterations in body position however this is highly unlikely as body position during the twitch measurements was strictly monitored at all phases of the training.

Another possibility is alterations in the elastic properties of the muscle, which is unlikely because of the short duration between measurements (7 weeks). A third possibilty is that of mechanical problems. Problems were encountered with the strain gauges in the shaft of the isometric dynamometer between training week 14 and 20 which necessitated recalibration of the system. Since the values observed for twitch torque were quite small they would be sensitive to small changes in torque calibration and it may be that this caused the observed decrease in twitch torque. The torque calibration however varied only 2% with the previous calibration file and therefore should not cause the magnitude of drop (10%) observed here. Another possibility is the contamination of the post training results due to a "low frequency fatigue" effect observed previously by Bigland-Ritchie et al. (1986) and Edwards et al. (1977). It is possible that training or strength testing the day prior to the twitch contraction measurements may have had a residual effect as this fatigue has been noted as long as 24 hours following exercise (Edwards et al., 1977). The finding of greater increases in joint positions of greatest flexion was interesting and may indicate a decrease in muscle elasticity with training as the muscle would tend not to be as "slack" at these joint positions and twitch tension would be transmitted to the bone more readily.

Since TPT and 1/2 RT were little affected by training, the changes in MRTD and MRTR were functions of the observed alterations in twitch torque. This relationship has been noted previously in our laboratory in the elbow flexors of untrained males and females and male bodybuilders (O'Hagan, Tsunoda and Sale, 1986). Alterations in

TPT and 1/2 RT occurred with joint angle; 1/2 RT increased significantly as the elbow was extended while TPT decreased with increasing joint angles. The increase in 1/2 RT with increasing joint angle has been noted previously in the plantar (Sale et al., 1982), and dorsi (Marsh et al., 1981) flexors of the ankle.

3. Conclusions

Several conclusions can be drawn from these results. First, strength gains measured on the weight device and isokinetic device were greater in the weight trained condition. Also, the increase in MW but not MI at 30 /s on the Cybex may indicate more general strength gains on the weight device at least in males. Secondly, the increases in muscle mass with this type of training occur to a greater extent in the brachialis than the biceps. Since the hypertrophy in this muscle was greater in the weight trained condition, this may account in part for the greater strength gains observed with weight training. Due to the variability of muscle biopsy sampling and the larger amount of hypertrophy observed in the brachialis, this hypertrophy did not translate to increases in muscle fibre area measured from tissue taken from the biceps. The increase in muscle mass was associated with an increase in isometric twitch torque. Twitch torque increased most at joint positions of greatest flexion. A possible explanation for this is a change in the elastic properties of the muscle. Lastly, strength training of this intensity and duration appears to have no effect on the twitch contraction and half-relaxation time; however, rates of torque development and relaxation increased in parallel with that of twitch torque.

B. Males vs Females

1. Results

To illustrate overall effects, the data are collapsed across one or more of the independent variables. In these cases, the combined means for gender, time of test or velocity of contraction are used in the post hoc analysis and given in the text.

a. Strength Performance Measures

Training-specific strength measurements were taken on both training apparatus. As well, non-specific strength measurements were made on a Cybex dynamometer at 4 velocities and custom-made isometric dynamometer at 7 joint positions.

i. Absolute Strength

Absolute strength measured on all devices was significantly greater in males than females. Changes in absolute strength on the training apparatus and Cybex in males and females are summarized in Figure 2-1. Measurements on the training devices were carried out at 2-3 week intervals. An example of the time course of strength changes is given in Figure 2-2 which illustrates 1 RM weight device values over time. A general linear increase in strength was observed between pre and post training on both the weight and isokinetic device. No evidence of a "plateau effect" was observed across the training period.

Changes in Cybex peak torque with training were velocity dependent. The females improved significantly at 30 and 120 °/s while males showed no change in peak torque at the slower velocities. The males decreased at the two higher velocities; significantly at 240 °/s (-7.33

Figure 2-1. Absolute changes in strength on the training devices and the Cybex dynamometer in males and females. Data are collapsed across velocity for the Cybex and isokinetic device. Significant increases in strength were observed in both groups (*) on the isokinetic and weight devices, $p<.05$. ** Males increased significantly more than females on the training devices while only females increased in Cybex peak torque, $p<.05$. Values are $\bar{X} \pm SE$.

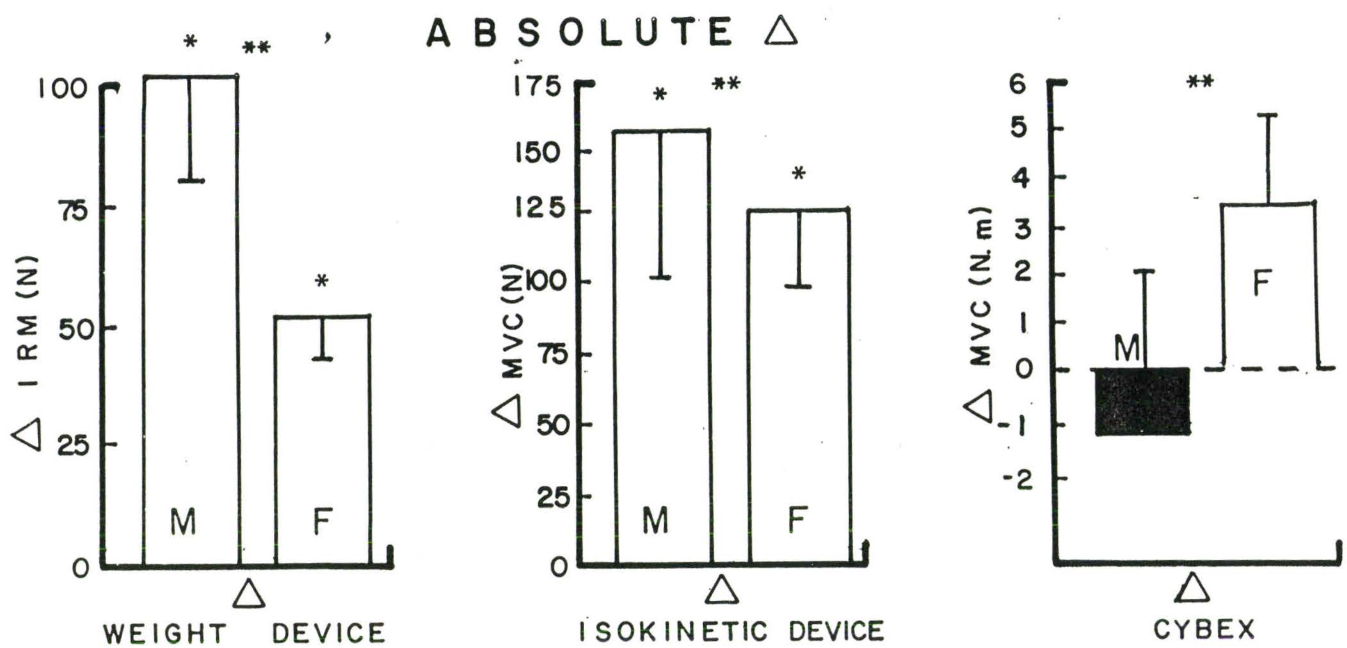
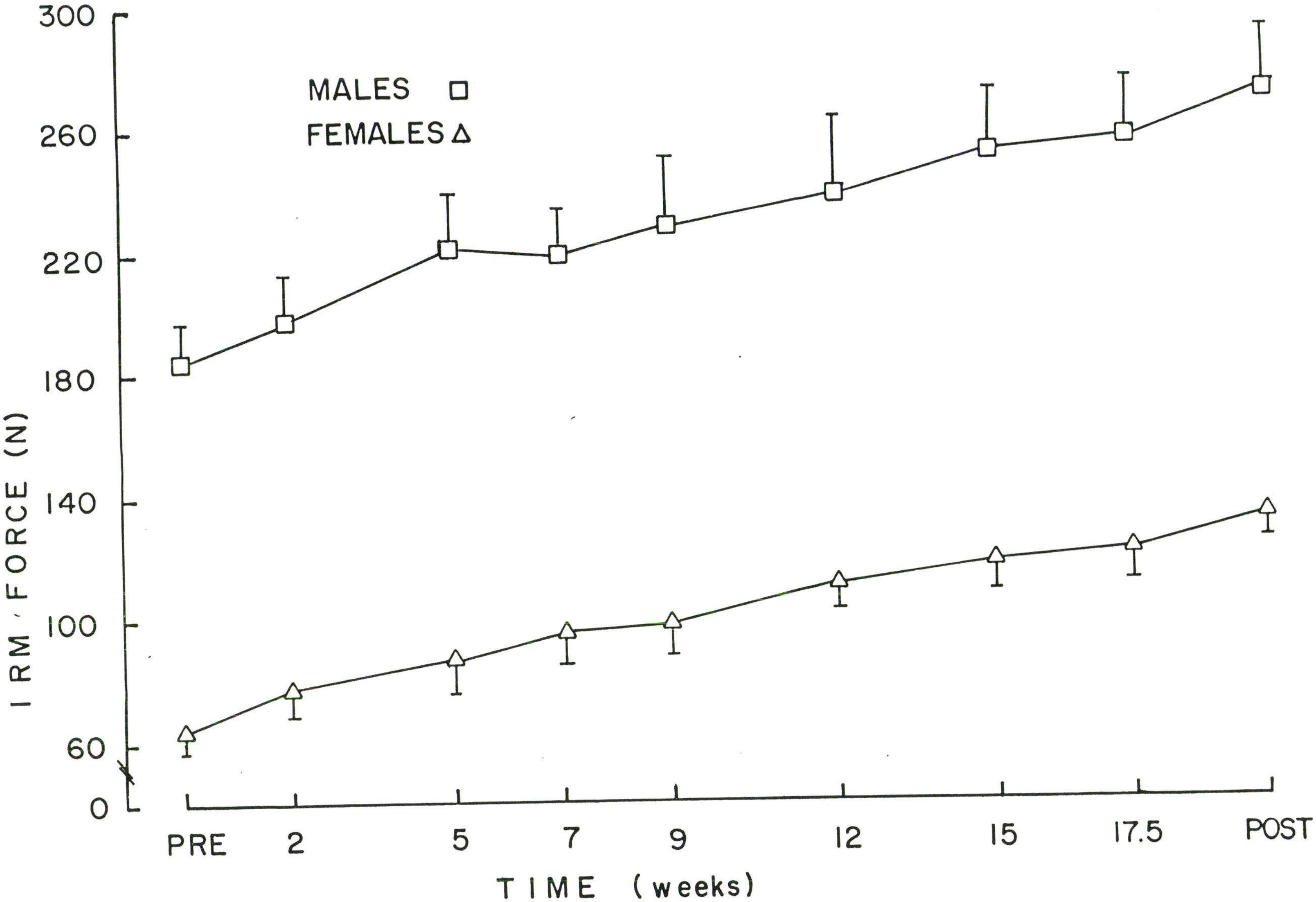

ABSOLUTE Δ
Δ 1 RM (N)
0
25
50
75
100
M
F
*
**
Δ
WEIGHT DEVICE
Δ MVC (N)
0
25
50
75
100
125
150
175
Δ
ISOKINETIC DEVICE
Δ MVC (N.m)
6
5
4
3
2
1
0
-1
-2
Δ
CYBEX

Figure 2-2. Changes in force across the training period on the weight device in males and females. A progressive linear increase in strength was observed in both groups on both training devices from pre to post training. Male values were significantly greater than females at all times, $p<.001$.

Values are $\bar{X} \pm SE$.


MALES
FEMALES
300
260
220
180
140
100
60
0
IRM FORCE (N)
PRE
2
5
7
9
12
15
17.5
POST
TIME (weeks)

N.m). The result was a significantly greater overall improvement in the females from pre to post training (Fig. 2-1). No change was observed in the females at 7 weeks of training while the males decreased significantly at 7 weeks then recovered post training. Cybex torque decreased significantly in males and females from 30 °/s to 120 °/s after which no change was observed (data collapsed across time).

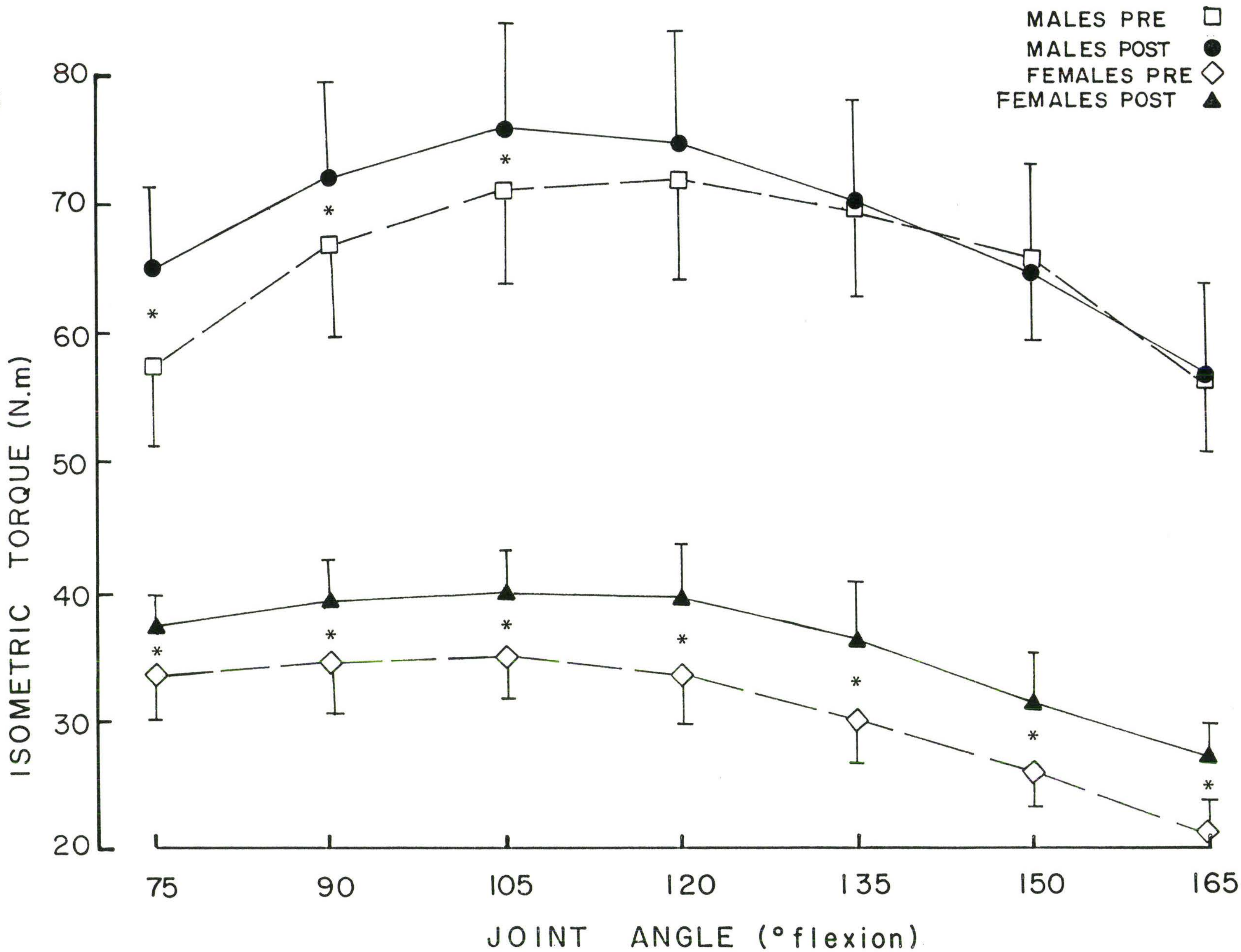
Peak torque measured on the isometric dynamometer showed an overall increase in both males and female groups from pre to post training with no change observed at 7 or 14 weeks of training (data collapsed across joint angle). Isometric MVC is depicted in Figure 2-3. For illustrative purposes, only the pre and post training values are given. A significant interaction was found between gender, joint position and time such that the female peak torque values increased significantly at all joint angles while the males increased only at 75, 90, and 105°. It was also observed that males and females differed in their overall torque "responses" as joint position was altered. Peak torque in the male group increased from 75 to 90° after which it plateaued to 120 and then decreased significantly to 165° whereas the female response showed no change from 75 to 135° after which it declined significantly at 150 and 165° (data collapsed across time and mode).

Absolute force (N) measured on the isokinetic device increased significantly in both males and females, from pre to post training (Figure 2-1). The increases were significantly greater at the slowest test velocity than the two faster velocities. Absolute increases in the males were significantly greater than the females (+150.8 N vs

Figure 2-3. Isometric peak torque across joint angles, pre and post training, in males and females. Male values were significantly greater than females' at all times, $p<.001$.

* Significant increase, from pre to post training, $p<.05$.

Values are $\bar{X} \pm SE$.


MALES PRE
MALES POST
FEMALES PRE
FEMALES POST
ISOMETRIC TORQUE (N.m)
80
70
60
50
40
30
20
75
90
105
120
135
150
165
JOINT ANGLE (° flexion)

+130.8 N - data collapsed across velocity)

The 1RM weight device values (Figure 2-2) increased significantly through the training period in both male and female groups. Again, the males increased to a greater extent than females (87.5 vs 70.0 N, Figure 2-1).

ii. Relative Strength

Relative values for the isometric MVC, isokinetic MVC and weight device 1RM were calculated and analysed as percentages of the pretest value. Due to the small changes observed with the Cybex measurements they were omitted from this analysis. Values in the text are given as percent changes from pretraining values.

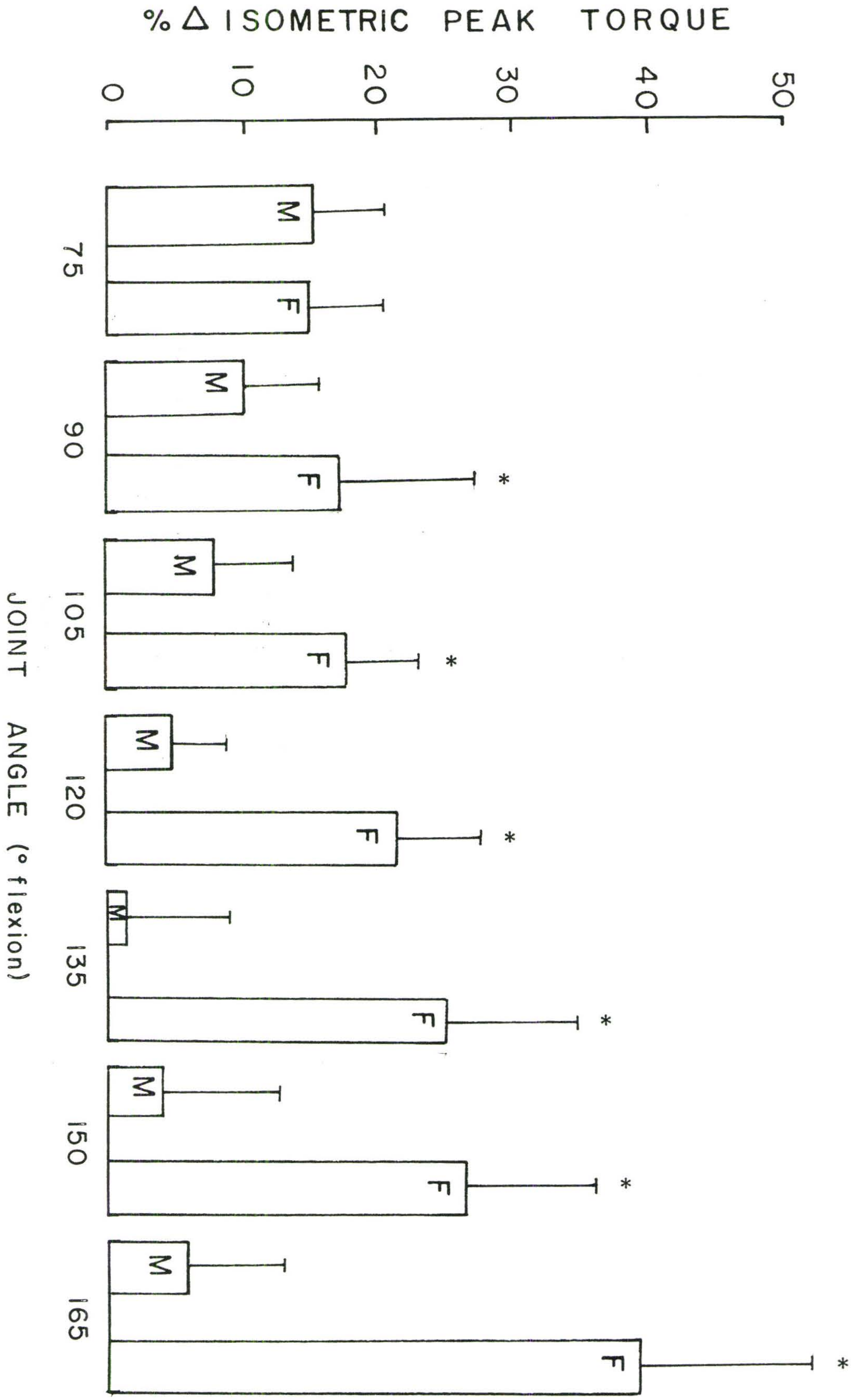
Relative values for isometric MVC's are illustrated in Figure 2-4. Increases for females were significantly greater than the males (122.5 vs 106.5% - data collapsed across joint position, $p<.02$). As in absolute isometric peak torque, a significant gender by joint angle by time interaction was observed. It revealed that the females increased in relative peak torque from 90° onwards with significantly greater increases observed at the most extended joint position while the males failed to show a significant increase at any of the joint angles. The pattern in the males was opposite to that with the increases (although non-significant) occurring at joint positions of greatest flexion.

Relative increases in MVC values on the isokinetic device as well as 1RM values on the weight device were significantly greater in females than males (Figure 2-5) Differences in isokinetic MVC increases were evident at 2 weeks (-3 vs 21.5%) and continued until post training (44.3 vs 99.3%, data collapsed across velocity). The

Figure 2-5. Relative changes in isometric peak torque from pretraining across joint angles.

* Significant increase from pretraining, $p<.05$.

Values are $\bar{X} \pm SE$.

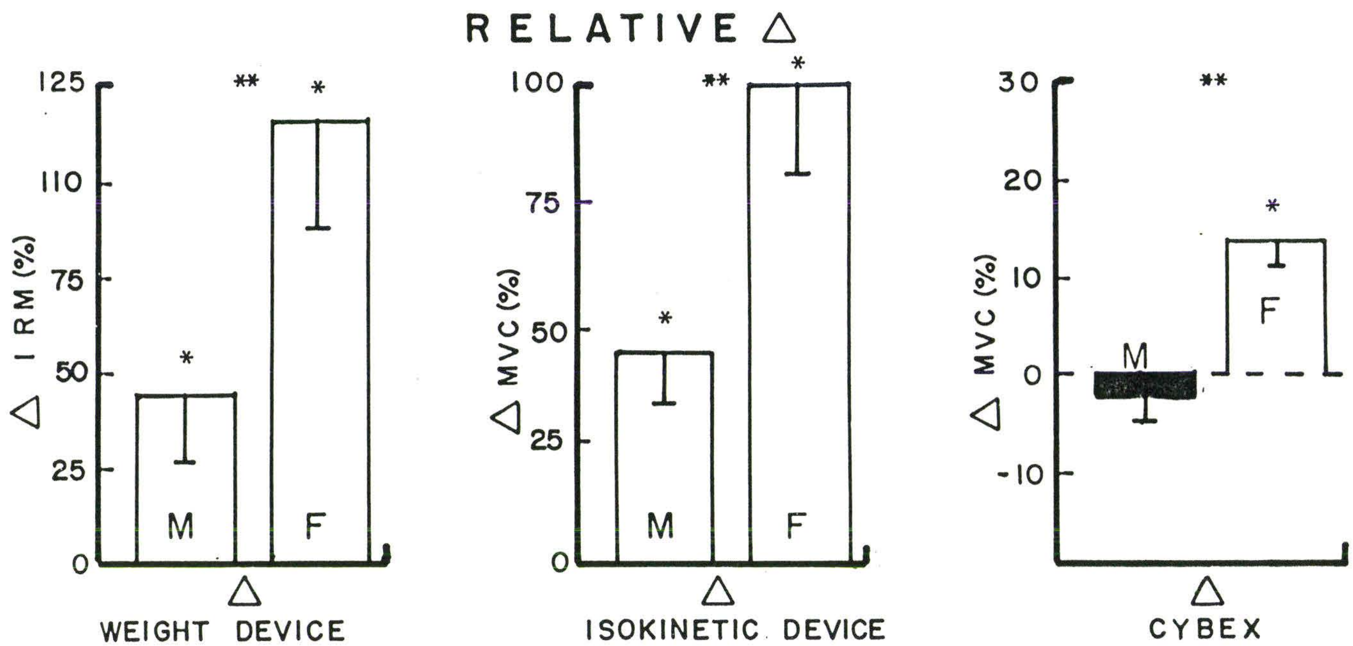


% Δ ISOMETRIC PEAK TORQUE
0
10
20
30
40
50
M
F
75
90
105
120
135
150
165
JOINT ANGLE (° flexion)
*

Figure 2-4. Relative changes in strength on the training devices and Cybex in males and females. Data are collapsed across velocity for the isokinetic device and Cybex. Values are $\bar{X} \pm$ SE.

* Significant increase from pretraining, $p<.001$.

** Female increase significantly greater than males, $p<.05$.


RELATIVE Δ
125
110
75
50
25
0
Δ 1 RM (%)
M
F
Δ
WEIGHT DEVICE
100
75
50
25
0
Δ MVC (%)
M
F
Δ
ISOKINETIC DEVICE
30
20
10
0
-10
Δ MVC (%)
M
F
Δ
CYBEX

greatest changes in relative isokinetic force occurred at the training velocity in both males and females (Figure 2-6). 1RM values rose by 116% in the females by post training while the males increased by 45.5%.

b. Gross Muscle Morphology

Biceps and brachialis cross-sectional areas were determined from computerized tomography (CT) scanning and summed to determime total flexor area. Data were analysed in absolute (cm^2) as well as relative (% of pretest) terms.

Absolute biceps, brachialis and total flexor areas were significantly greater in males than females both pre and post training. Values are depicted in Figure 2-7.

Both male and female groups showed significant increases in total flexor cross-sectional area with no overall difference between groups (3.31 cm^2 in males, 3.07 cm^2 in females). This was a result of significant overall increases in bicep (.97 cm^2) and brachialis (2.22 cm^2) areas. There were no differences between groups in absolute increases in biceps or brachialis area.

Total flexor area expressed as percentage of the pretest value increased significantly in both males and females with a trend ($p<.10$) towards greater increases in the females (13.1 vs 7.6%). Biceps area increased by 9.9% overall, with no difference between males and females while brachialis area increased 41.9% with a trend ($p<.12$) toward greater increase in the females (26.2 vs 15.7%). The overall relative increase in brachialis area (41.9%) was significantly greater than that of biceps (9.9%).

Figure 2-6. Relative increases in isokinetic force in males and females at 3 velocities (1-fastest, 6-slowest). Increases were significantly greater in females at all velocities, $p<.05$. Values are $\bar{X} \pm SE$.

* Significant increase from pretraining, $p<.05$.

** Significantly greater increase than the adjacent velocity, $p<.05$.

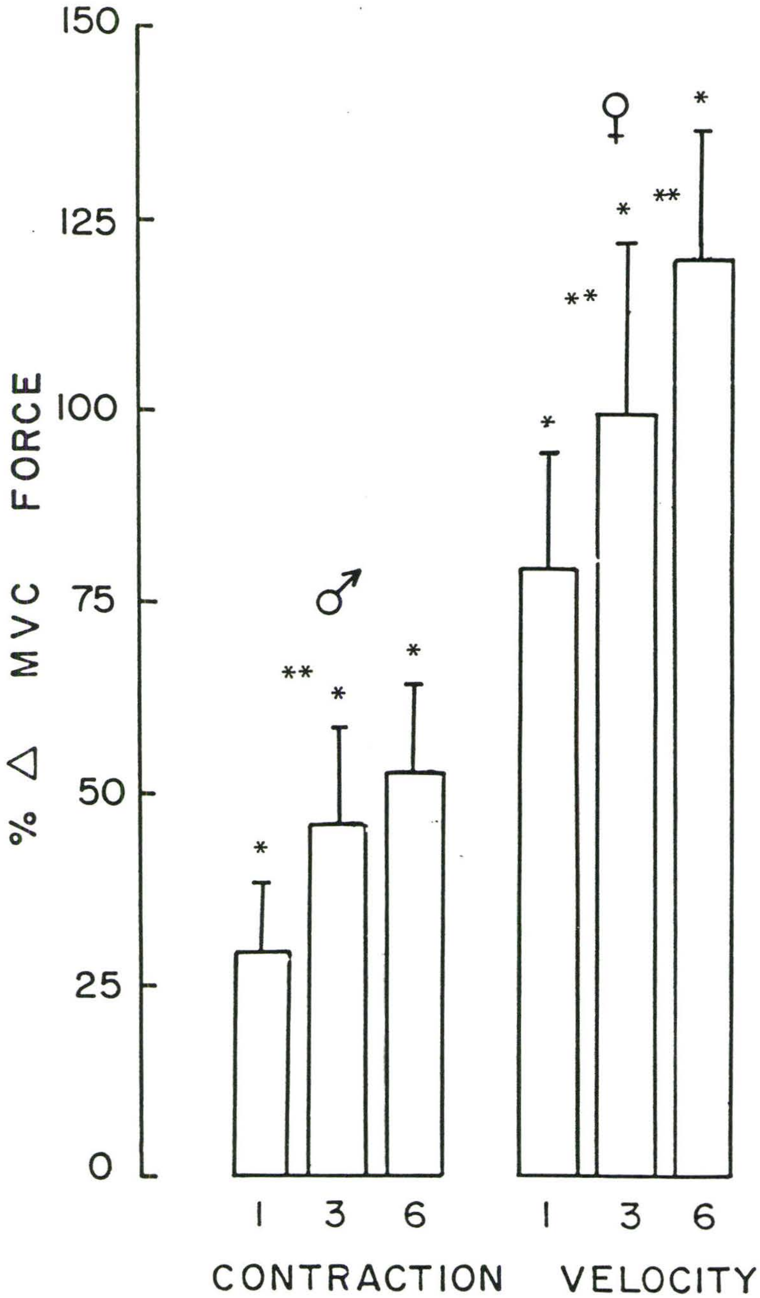
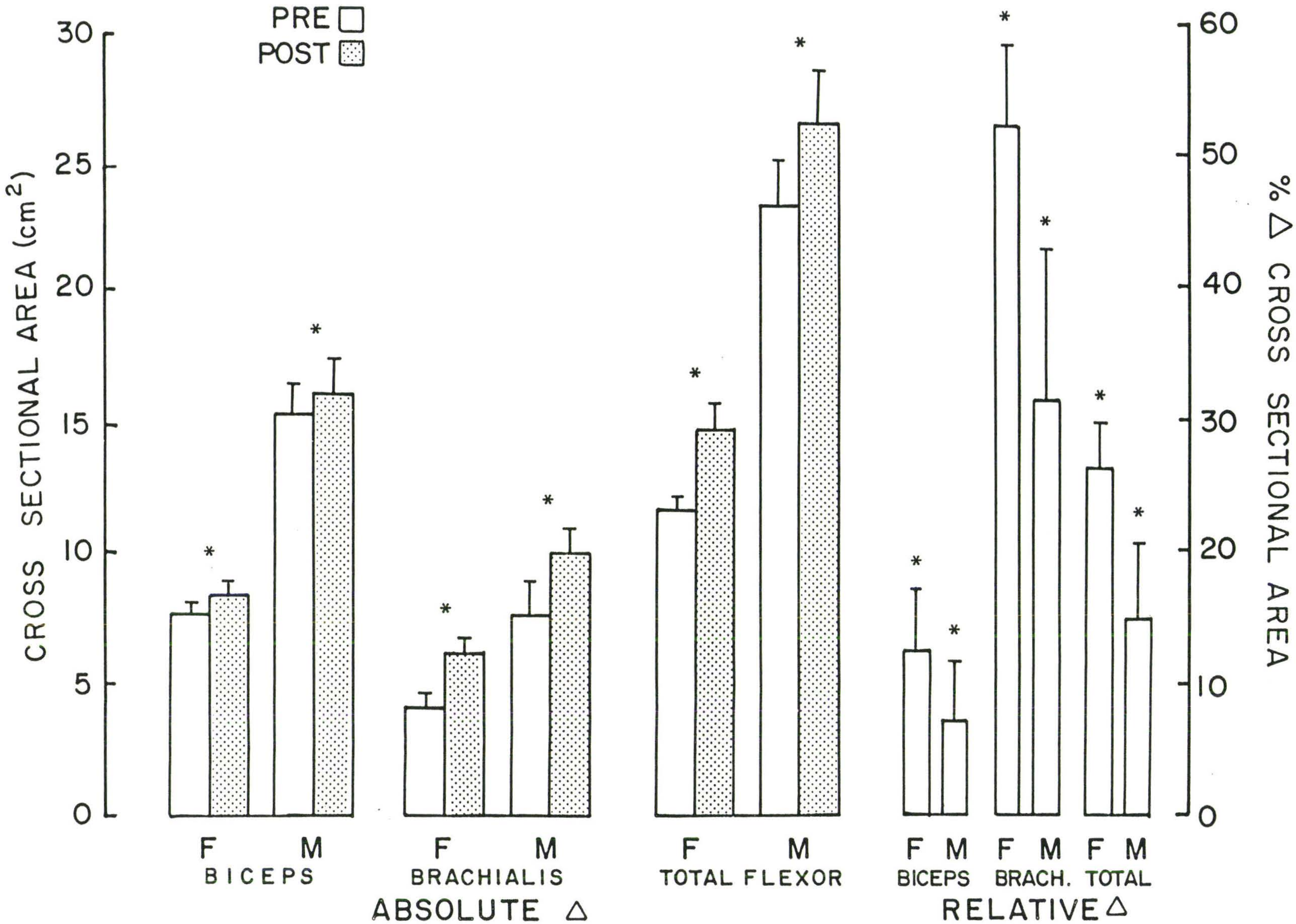

150
125
100
75
50
25
0
% Δ MVC FORCE
♂
♀
1 3 6
1 3 6
CONTRACTION VELOCITY

Figure 2-7. Absolute and relative increases in biceps, brachialis and total flexor cross-sectional areas in males and females.

* Significant increase, pre to post training, $p<.05$. Values are $\bar{X} \pm SE$.


PRE
POST
CROSS SECTIONAL AREA (cm²)
30
25
20
15
10
5
0
% △ CROSS SECTIONAL AREA
60
50
40
30
20
10
0
F M
BICEPS
F M
BRACHIALIS
F M
TOTAL FLEXOR
ABSOLUTE △
F M F M F M
BICEPS BRACH. TOTAL
RELATIVE △

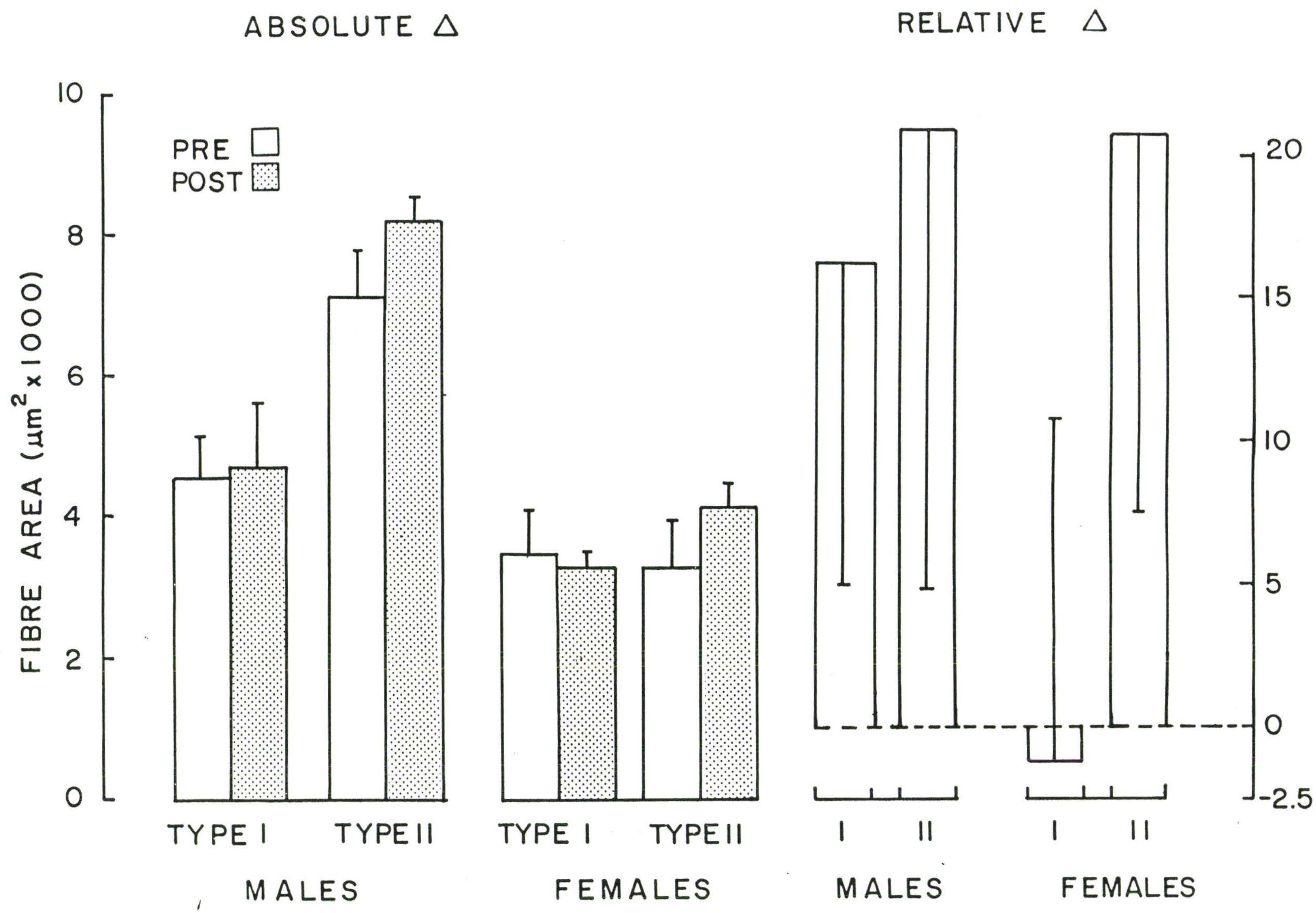
c. Fibre Areas

Absolute fibre areas (μm^2) did not increase significantly ($p<.16$) following the training period, although fibre areas were greater in all but the female Type I fibres (Figure 2-8). Males had significantly larger fibre areas than females. Type II fibres were significantly larger than type I fibres in the males while no difference existed between the fibre types in the females. Although no main effect was observed for training there was a definite trend ($p<.08$) for the Type II fibres to show a greater hypertrophy response with training (+564.3 vs -296.1 μm^2 in females, +518.4 μm^2 vs +105.4 μm^2 in males).

When fibre areas were expressed as a percentage of the pretest value, the increases approached significance ($p<.07$, Figure 2-8). Males increased by 18.7% and females by 9.8% (data collapsed across fibre type). Type II fibres tended to hypertrophy more than Type I fibres ($p<.06$), showing an overall increase of 20.8% compared to 2.6% in the Type I fibres (data collapsed across gender).

Fibre area ratios were calculated from the subjects' mean fibre areas and expressed as Type II : Type I fibre area ratios. Males had greater Type II : Type I fibre area ratios than females in all conditions. The greater increases observed in Type II fibres resulted in a significant overall increase in fibre area ratios; from 1.61 to 1.66 in the males and from 1.01 to 1.25 in the females (data collapsed across mode, $p<.057$).

Figure 2-8. Absolute and relative changes in Type I and Type II fibre areas in males and females. Values are $\bar{X} \pm$ SE.


ABSOLUTE Δ
RELATIVE Δ
PRE
POST
FIBRE AREA (μm² x 1000)
0
2
4
6
8
10
TYPE I
TYPE II
TYPE I
TYPE II
MALES
FEMALES
I
II
I
II
MALES
FEMALES
% Δ FIBRE AREA
-2.5
0
5
10
15
20

Involuntary Contractile Property Measurements

Peak twitch torque (PT), 1/2 relaxation time (1/2 RT), time to peak torque (TPT), maximum rate of torque development (MRTD) and maximum rate of torque relaxation (MRTR) were determined from maximal twitch contractions. Measurements were made on an isometric dynamometer at joint positions ranging from 75 to 165° (180°= full extension).

Twitch peak torque was analysed both in absolute (N.m) as well as relative (% of pretest) terms. Absolute PT (Figure 2-9) was significantly greater in males than females. PT did not change from pretraining (5.46 N.m) to 7 weeks (5.63 N.m) and increased significantly at 14 weeks (6.52 N.m) after which it declined post training (6.1 N.m). PT remained significantly elevated, post training, in males at 75, 90 and 120° while female post training values did not differ from pretraining values. The greatest increases in torque were observed at joint positions of greatest flexion (75 and 90°). PT increased significantly as the elbow was extended (data collapsed across time). In males, PT increased from 75° (3.44 N.m) to 120° (9.9 N.m) after which it increased to a lesser extent and peaked at 165 (11.1 N.m). Females increased from 75° (1.98 N.m) to 90° (3.03 N.m) after which no significant change occurred.

Unlike the absolute values for PT, relative PT increased significantly at 14 weeks (37.2%) and remained significantly greater post training (29.9% -data collapsed across gender and joint angle). Values are illustrated in Figure 2-10. The greatest increase in relative PT occurred at the joint positions of greatest flexion. Only at 75° (48.8%), did PT increase after 7 weeks training. At 14 weeks,

Figure 2-9. Twitch peak torque across joint angles, pre 7 weeks, 14 weeks and post training in males and females.

* 14 week value significantly greater than pretraining, $p<.05$.

** Post training value significantly greater than pretraining, $p<.05$.

Values are $\bar{X}$. SE bars are ommitted for clarity.

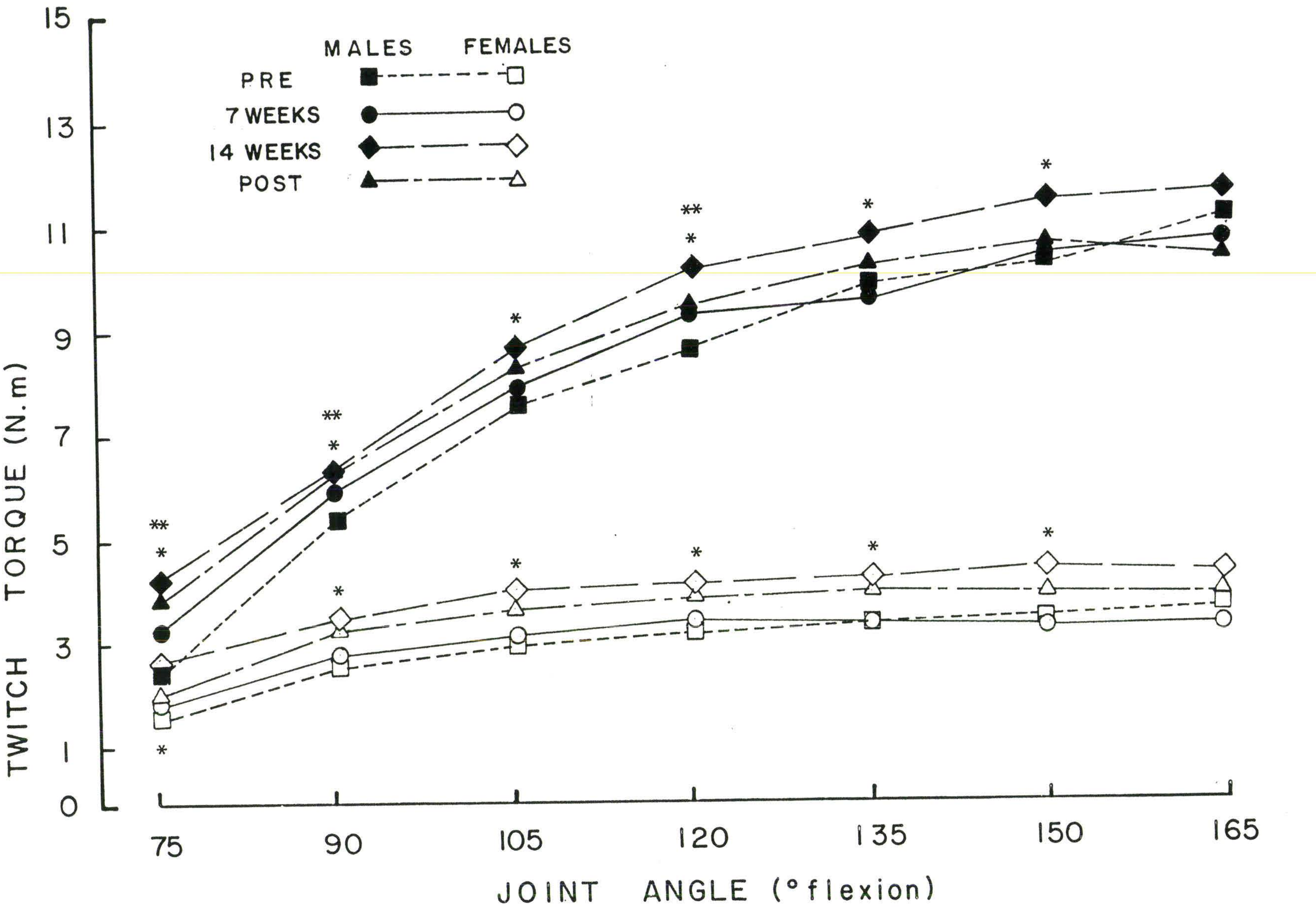
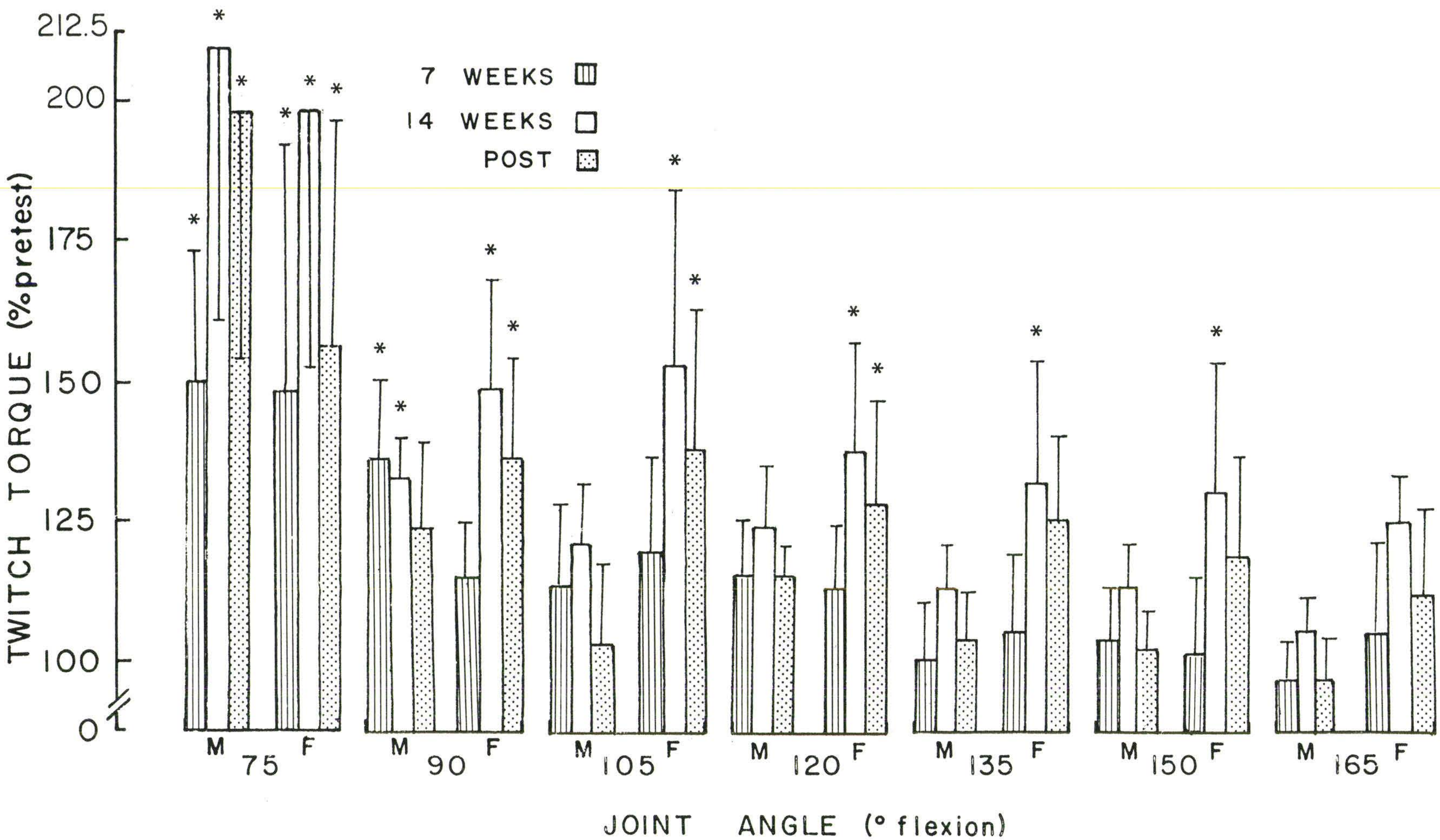

MALES
FEMALES
PRE
7 WEEKS
14 WEEKS
POST
TWITCH TORQUE (N.m)
JOINT ANGLE (° flexion)
0
1
3
5
7
9
11
13
15
75
90
105
120
135
150
165

Figure 2-10. Relative twitch peak torque across joint angles at 7 weeks, 14 weeks and post training in males and females. Values are $\bar{X} \pm SE$.

* Significant increase from pretraining, $p<.05$.


TWITCH TORQUE (% pretest)
212.5
200
175
150
125
100
0
7 WEEKS
14 WEEKS
POST
M 75 F
M 90 F
M 105 F
M 120 F
M 135 F
M 150 F
M 165 F
JOINT ANGLE (° flexion)

relative PT increased 102% at 75°, 38% at 90° and 105° and 31% at 120° after which no significant change was observed (data collapsed across gender). PT remained significantly elevated at 75 (96.8%) in the male group, and at 75 (57.3%), 90 (36.2%), 105 (38.5%) and 120° (29.3%); however, no overall difference was observed between groups at this point.

TPT values were not affected by gender and very little by training. TPT increased significantly at 75° from pre (58.2 ms) to post (66.3 ms) training (data collapsed across gender and mode). TPT was affected by changes in joint position and decreased significantly across all joint angles from 90° (63.3 ms) to 150° (53.8 ms -data collapsed across gender, mode and time).

Half RT values were affected by gender and joint position and to a lesser extent, training. Values are given in Figure 2-11. Half RT was greater in females than males in almost all conditions and times. The only exceptions were pre, 14 weeks and post training values at 150 and pre and 14 week training values at 165 . Half RT increased significantly from 75° (59.9 ms) to 135° (85.6 ms) after which it plateaued and remained unchanged to 165° (86.4 ms -data collapsed across gender). Half RT decreased at 150 and 165° after 14 weeks training then returned to the pretraining value range, post training (data collapsed across gender).

Alterations in MRTD and MRTR paralled the changes in PT. Males had significantly greater MRTD than females at all joint positions (Figure 2-12a, b). MRTD increased significantly as the elbow was extended; in males up to 135° after which it plateaued and in females up to 105° after which only slight increases were observed (data

Figure 2-11. 1/2 relaxation time across joint angles, pre 7 weeks, 14 weeks and post training in males and females. Female values were significantly greater than males, overall, $p<.05$. Significant overall decrease was observed at 14 weeks, $p<.05$.

Values are $\bar{X}$. SE bars are omitted for clarity.

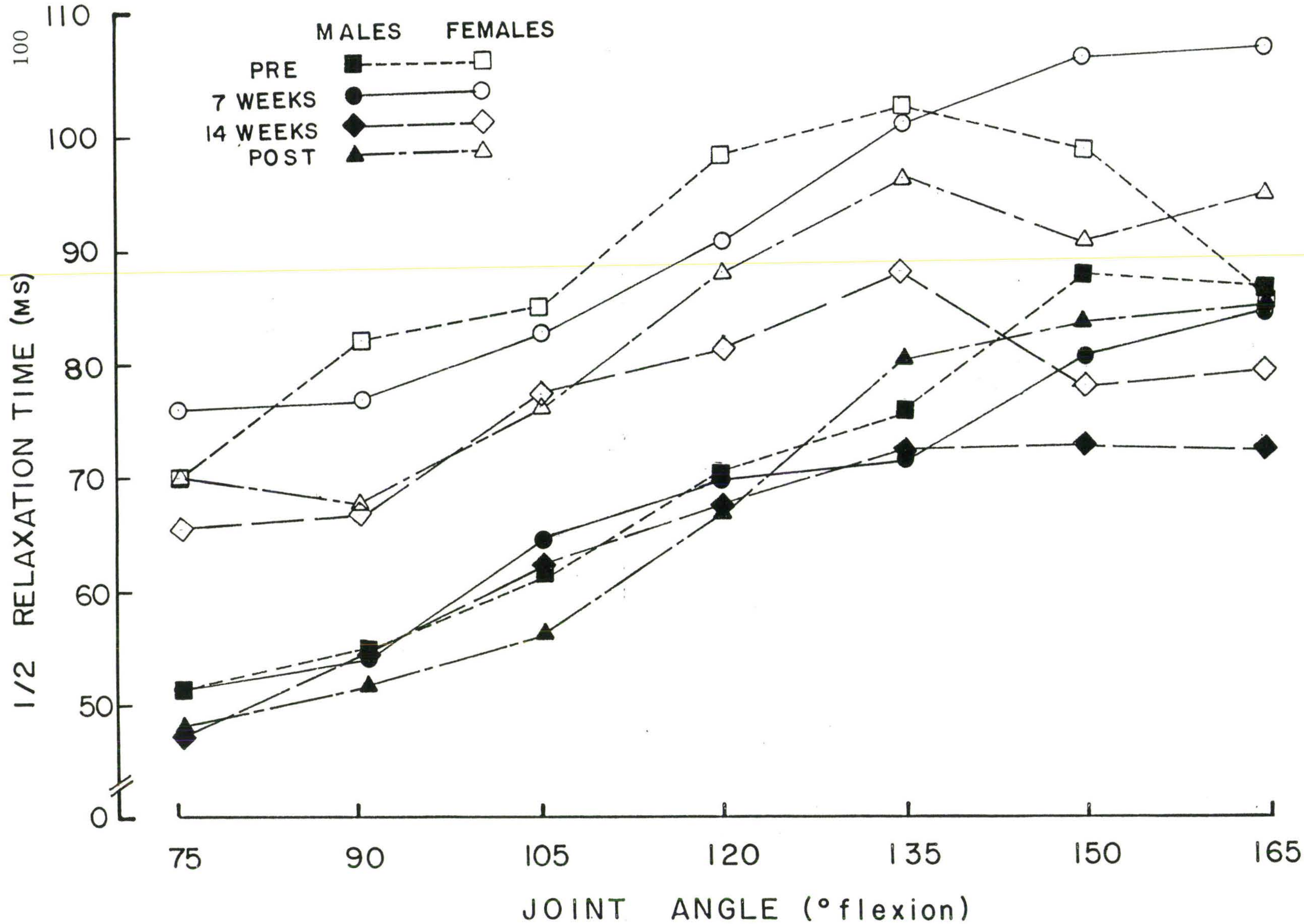

MALES FEMALES
PRE
7 WEEKS
14 WEEKS
POST
110
100
90
80
70
60
50
0
1/2 RELAXATION TIME (MS)
75
90
105
120
135
150
165
JOINT ANGLE (°flexion)

Figure 2-12a. Maximum rate of torque development across joint angles, pre, 7 weeks, 14 weeks and post training in females. Values are $\bar{X} \pm SE$.

* Significant increase from pretraining, $p<.05$.

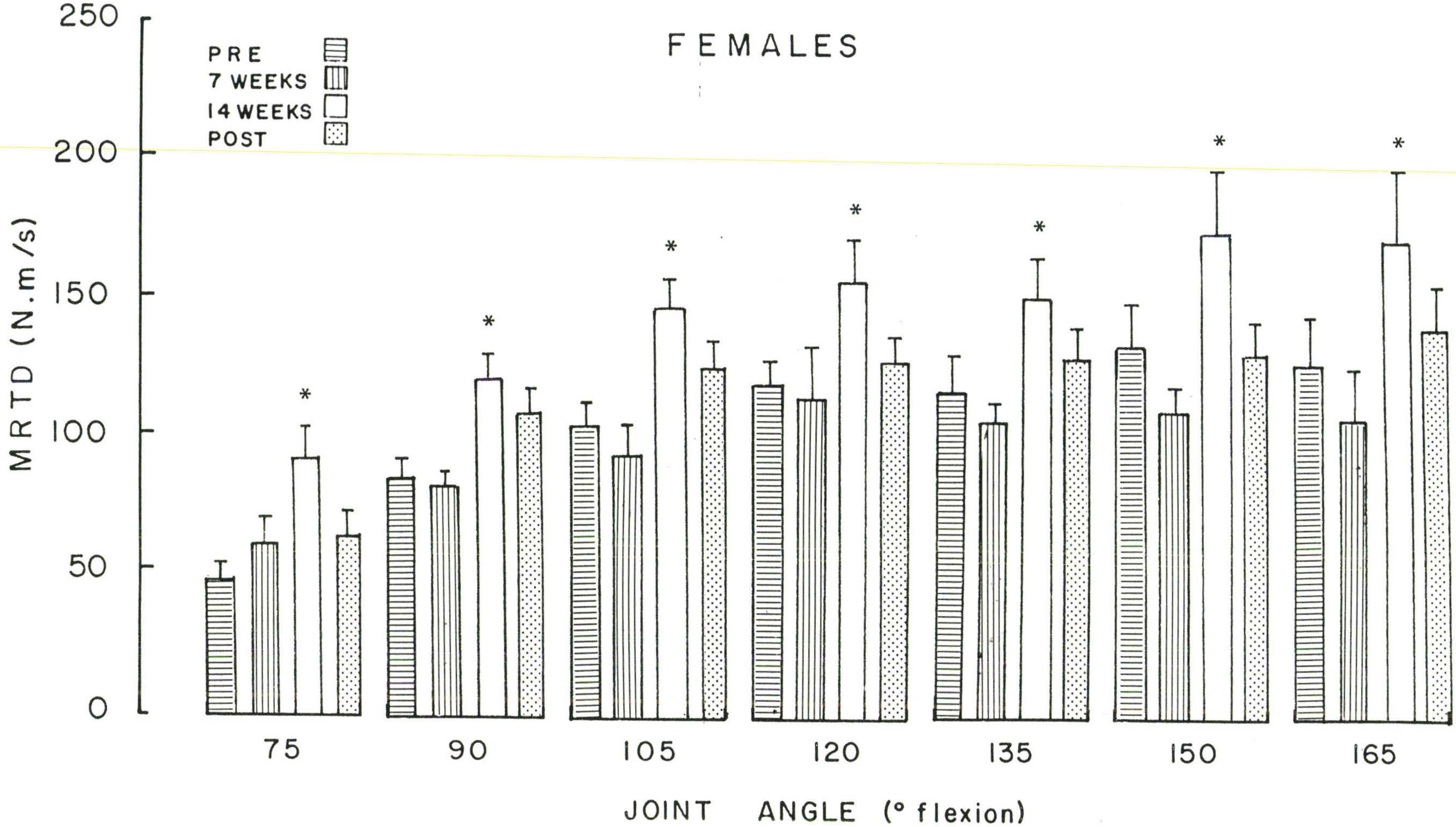
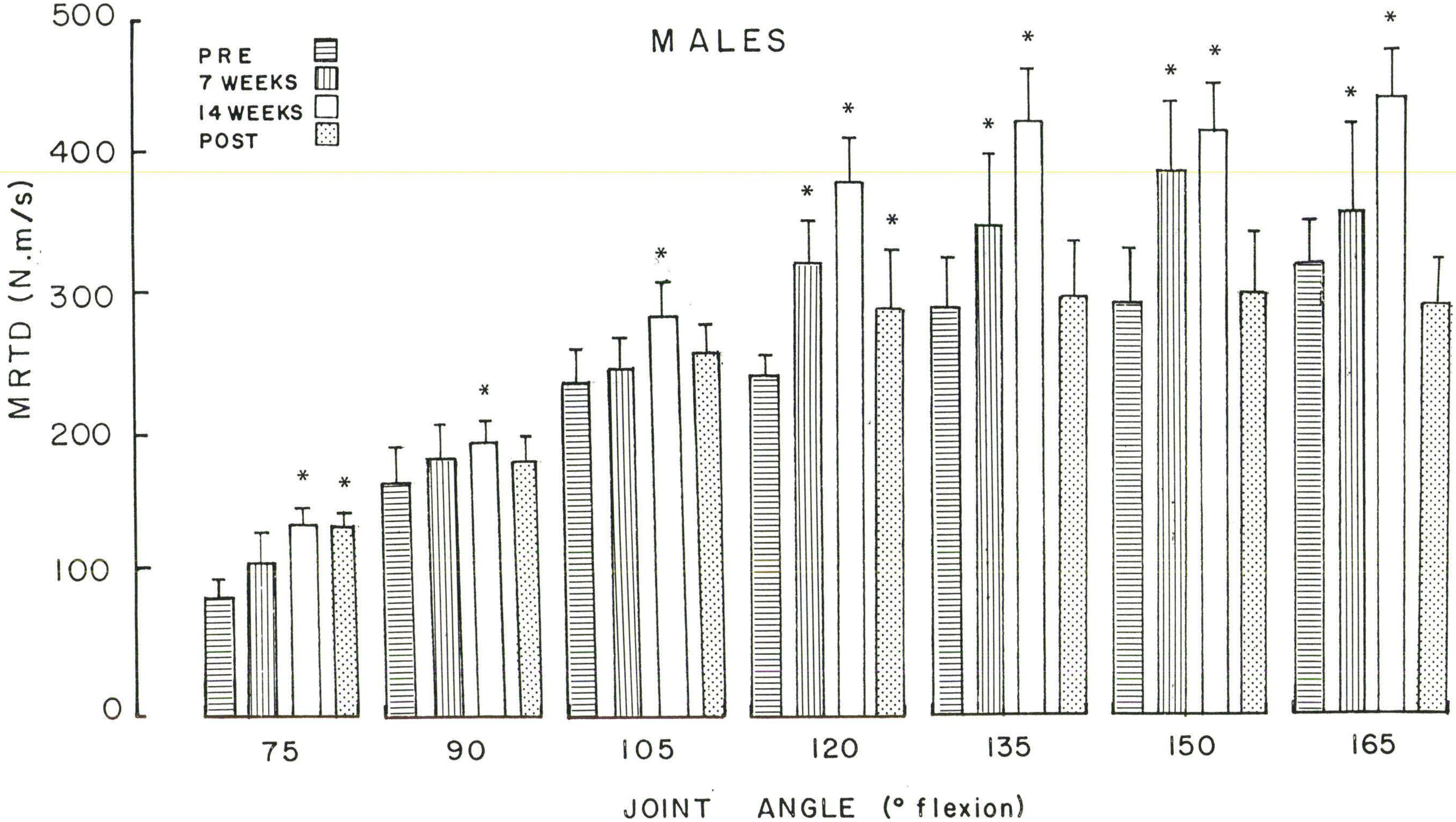

FEMALES
PRE
7 WEEKS
14 WEEKS
POST
MRTD (N.m/s)
250
200
150
100
50
0
75
90
105
120
135
150
165
JOINT ANGLE (° flexion)

Figure 2-12b. Maximum rate of torque development across joint angles, pre, 7 weeks, 14 weeks and post training in males. Values are $\bar{X} \pm SE$.

* Significant increase from pretraining, $p<.05$.


MALES
PRE
7 WEEKS
14 WEEKS
POST
MRTD (N.m/s)
0
100
200
300
400
500
*
75
90
105
120
135
150
165
JOINT ANGLE (° flexion)

collapsed across time). There was an overall increase in MRTD from pre to 14 weeks of training after which MRTD decreased, remaining slightly, but not significantly higher than pretest values. These increases were most evident in the males, and specifically the MI condition, which increased by 142 N.m/s compared to a 46.1 N.m/s increased in the MW condition. In the females, the FW condition remained elevated (+21.8 N.m/s) while the FI condition returned towards pretraining values (+4.2 N.m/s)

MRTR was also affected by gender and joint position. MRTR was significantly greater in males than females (Figure 2-13a,b). In males, MRTR increased steadily from 75 (61.6 N.m/s) to 150° (148.1 N.m/s) after which it declined slightly; whereas females showed smaller increases with no significant change occurring until 150° (data collapsed across time). The same changes occurred in MRTR across time as was observed in MRTD and PT. MRTR increased from pretraining (67.9 N.m/s) to 14 weeks (99.4 N.m/s) then declined post training (70.3 N.m/s, data collapsed across gender, joint angle). As was observed with PT, MRTR at lower joint angles (75°, 90°) remained elevated at post training.

2. Discussion

The inclusion of females in this training study was unique for several reasons. Firstly, the duration of the training period (20 weeks) was considerably longer than that of previous studies comparing male and female training responses (e.g. 10 week of training in Wilmore, 1974). Secondly, although previous studies have examined

Figure 2-13a. Maximum rate of torque relaxation across joint angles, pre, 7 weeks, 14 weeks and post training in females. Values are $\bar{X} \pm SE$.

* Significant increase from pretraining, $p<.05$.

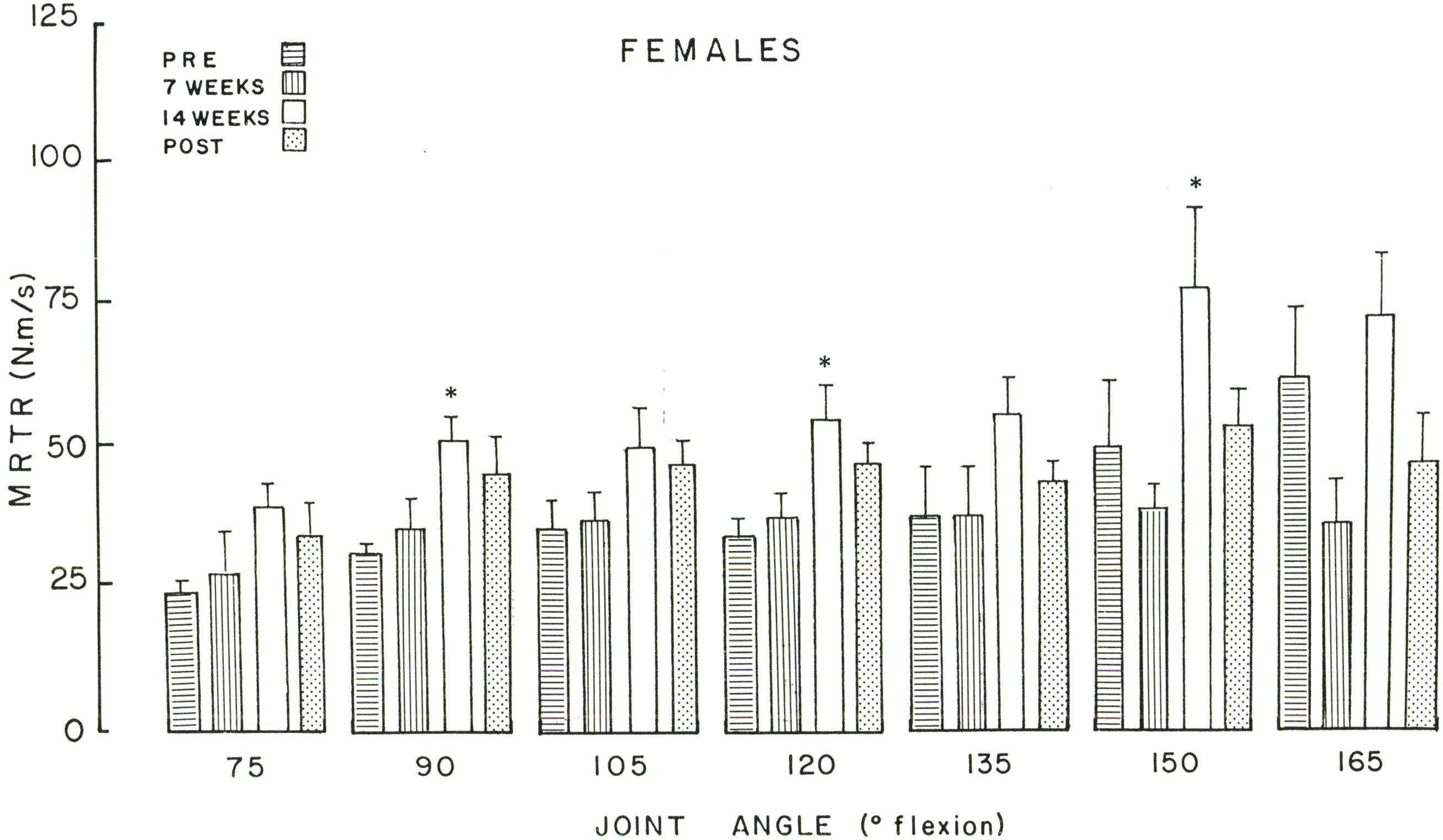
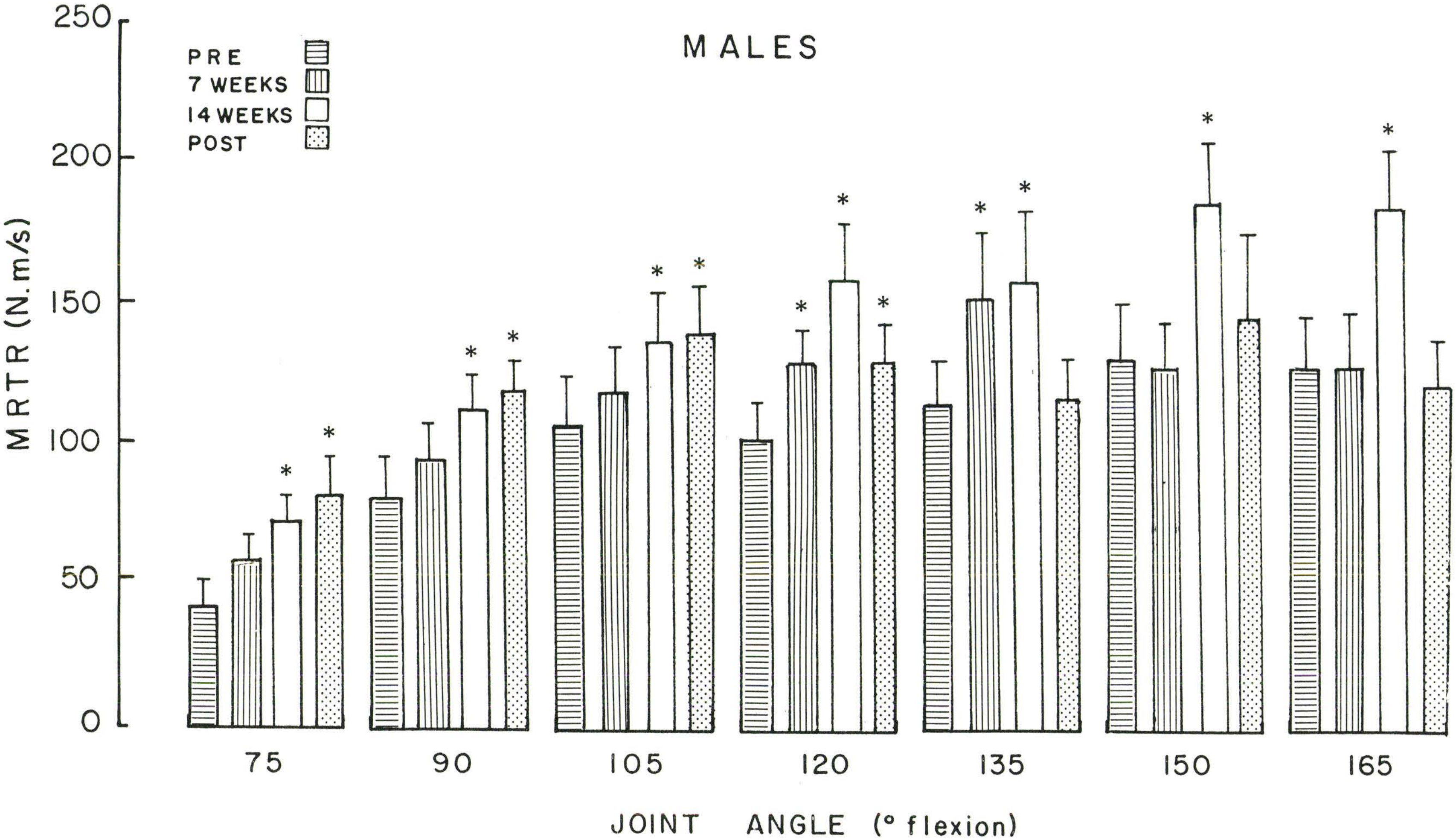

FEMALES
PRE
7 WEEKS
14 WEEKS
POST
MRTR (N.m/s)
125
100
75
50
25
0
*
75
90
105
120
135
150
165
JOINT ANGLE (° flexion)

Figure 2-13b. Maximum rate of torque relaxation across joint angles, pre, 7weeks, 14 weeks and post training in males. Values are $\bar{X} \pm SE$.

* Significant increase from pretraining, $p<.05$.


MALES
PRE
7 WEEKS
14 WEEKS
POST
MRTR (N.m/s)
250
200
150
100
50
0
75
90
105
120
135
150
165
JOINT ANGLE (° flexion)

limb girth and skinfold thickness (Wilmore, 1974; O'Shea and Wegner, 1981), none have used CT scanning or fibre area measurements which give better resolution of the adaptations induced by strength training in the muscle itself. In this respect, a better study of the hypertrophy response in males and females is possible. Thirdly, the measurement of involuntary contractile properties permitted the study of the response of these properties with training as well as the possibility of differences in contractile properties between males and females.

a. Strength Performance Measurements

Although absolute gains in strength in males exceeded those of females in all but Cybex measurements, females showed significantly greater relative gains in strength on all devices. In college age males and females, strength trained over a 10 week period, Wilmore (1974) found greater relative strength gains in the females. In the same population, 10 weeks of circuit training produced greater relative and absolute increases in strength in the females (Wilmore et al. 1978). These results were supported by those of O'Shea and Wegner (1981) who found comparable absolute and greater relative strength gains in females. A probable explanation is the relatively "untrained" state at which the females begin training. Habituated activity levels in the females may have been lower than the males, particularly participation in activities involving heavy lifting; thus, they started the training period further from their "potential" than the males. This would be particularily true of an upper body muscle group, as females are relatively weaker in upper body strength

(O'Shea and Wegner, 1981). It may be that the greater relative gain in strength was due to greater neural adaptation on the part of the females. However, preliminary measurements of interpolated twitches in the subjects indicated almost complete activation of motor units in both males and females. As well, strength per unit cross-sectional area muscle has been shown to be the same in females and males (Ikai and Fukunaga, 1968) which would also tend to refute this assertion. However, the same authors observed considerable variablility within groups and it is known that this relationship can be altered by training (Ikai and Fukunaga, 1970) supporting the idea of a considerable "neural" component to the expression of strength (for a review see Sale, 1986). It is also possible that the females were unable to optimize the firing frequency of motor units as the interpolated twitch method gives no indication of the level of firing frequency (Bigland-Ritchie et al., 1986). The finding that increases in muscle cross-sectional areas were the same in males and females may also provide an explanation as the same increase in absolute tension producing capbilities in the female muscle would cause a greater increase in terms of relative strength. What is important from a practical standpoint is that females have the capacity for significant increases in strength although the question of absolute capacity for strength gain would take a longer term study.

b. Muscle and Fibre Areas

Males and females had similar relative increases in muscle and fibre size. The absolute increase observed in brachialis area was in fact larger in FW than MI and the relative increase in brachialis and total flexor cross-sectional area was greater (although non-significantly) in females. This finding supports that of Wilmore et al. (1978) who observed similar gains in lean body mass in males and females exposed to a 10 week circuit training program. Other studies (Brown and Wilmore, 1974, Oyster, 1979) however, have observed a lack of significant hypertrophy accompanying the increases in strength in females undergoing strength training. These were done on female athletes which may explain the lack of hypertrophy response and again these studies are limited by the fact that only girth measurements were taken. Krahenbul, Archer and Petit, (1978) found no relationship between serum testosterone levels and strength gain in trained females. Animal studies have also shown that hypertrophy is possible, independent of endogenous anabolic hormones and that muscle tension is the overriding factor in the expression of muscle hypertrophy (Goldberg et al., 1975). It is apparent from these results, that females have the capacity for significant hypertrophy when exposed to a training program the same as that of males. These increases in muscle mass may be limited over the long term however, by factors such as fibre number and anabolic hormones.

c. Involuntary Contractile Properties

Twitch peak torque was greater in the males as was to be expected from their greater muscle mass. Absolute increases in PT were greater in the males at 14 weeks and post training, however no difference was observed between males and females in relative changes in PT supporting the lack of difference between groups in muscle area increases. Again, MRTD and MRTR values mirrored those of peak torque, both in terms of gender differences and changes with training, indicating that PT rather than the time related variables is the critical factor in the expression of MRTD and MRTR. Little change was observed with training in either of the time related contractile characteristics. The greater 1/2 RT observed in females agrees with previous studies in human triceps surae (Belanger and McComas, 1981). The mechanism of this effect has yet to be elucidated.

3. Conclusions

Several conclusions can be drawn from these results. First, although females show smaller absolute gains in strength and remain significantly "weaker" than males, their relative capacity for strength increase is impressive and is significantly greater than that of males on all of the testing devices. Secondly, females are capable of muscle hypertrophy in an isolated muscle group comparable to that of males over a 6 month training period. This hypertrophy response is greater in the brachialis than the biceps as discussed in the previous section. Although fibre areas did not show a statistically significant increase due to training, this muscle hypertrophy is probably due to the hypertrophy of existing muscle fibres. Lastly, the increases observed in PT may be ascribed to the increases in muscle mass; however, the fluctuation from 14 weeks to post training is difficult to account for but may be due to a low frequency fatigue effect. Strength training did not affect the time-related contractile properties of human muscle; however, it would seem that females have a longer 1/2 RT than males, the reason for which is unclear.

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Appendix A, 1-15. Tabled data for isokinetic vs weight trained conditions.

Appendix A-1. Cybex peak torque (N.m) at pre, 7 weeks and post training in isokinetic and weight conditions.

Velocity	Time of Test					
(°/s)	Pre		7 weeks		Post	
IK	$\bar{X}$	SE	$\bar{X}$	SE	$\bar{X}$	SE
30	46.8	3.9	43.9	4.2	50.8	3.7
120	39.1	3.1	35.3	2.7	39.1	2.5
180	34.8	3.9	32.6	2.3	34.6	2.3
240	36.5	4.0	32.4	2.3	31.6	2.2
Weight						
30	47.2	3.1	44.2	2.6	52.4	3.0
120	36.3	2.8	39.4	2.5	40.7	3.0
180	34.3	3.5	32.0	2.8	35.6	2.7
240	35.5	2.7	32.7	2.1	34.4	3.0

Values are $\bar{X} \pm$ SE.
IK denotes isokinetic device.

App. A-2. Isometric dynamometer peak torque (N.m) in isokinetic and weight conditions from 75 to 165° elbow flexion (180° = full extension).

Joint Angle degrees	Pre $\bar{X}$	SE	Time of Test 7 weeks $\bar{X}$	SE	14 weeks $\bar{X}$	SE	Post $\bar{X}$	SE	% Change
IK									
75	45.5	4.5	46.5	5.0	48.6	4.0	51.6	3.5	15.4
90	50.9	6.2	49.2	4.8	53.3	4.2	54.7	4.5	11.1
105	53.4	6.3	51.6	5.8	56.0	5.2	57.8	5.1	12.7
120	52.1	6.7	53.1	5.9	54.1	4.5	55.8	6.5	11.4
135	49.5	6.0	50.4	5.2	50.9	5.1	51.3	5.8	9.0
150	45.9	5.7	44.0	5.4	46.9	5.1	45.1	5.3	3.9
165	37.7	5.1	35.9	4.6	37.7	4.3	40.6	4.4	21.9
Weight									
75	45.7	5.6	47.0	5.0	51.1	5.1	51.1	4.9	13.9
90	50.6	5.6	53.5	5.2	57.0	6.0	56.8	4.9	15.7
105	52.9	6.1	55.6	4.9	58.5	6.2	58.4	6.5	12.6
120	53.4	5.7	55.4	5.4	58.4	4.4	58.7	5.6	14.3
135	50.2	5.8	53.1	4.9	53.6	4.5	55.4	5.5	17.4
150	45.8	5.4	48.8	5.1	48.4	4.1	50.9	5.0	25.9
165	39.6	5.9	39.9	4.1	43.6	4.0	43.3	5.0	22.4

Values are $\bar{X}$ ± SE.
Significant overall increase was observed from pre to post training.
IK denotes isokinetic device.

App. A-3. Isokinetic device MVC (N) in isokinetic and weight conditions at 3 velocities from pre to post training (1-fastest, 6-slowest).

Velocity		Pre	Time (weeks) 2	5	7	9	12	15	17.5	Post
IK										
1	$\bar{X}$	175.3	171.2	192.6*	188.3	193.6	210.7	210.7	242.6	236.9
	±SE	16.6	21.4	15.3	21.0	18.3	19.6	27.6	25.0	28.5
3	$\bar{X}$	196.4	213.2*	236.8	235.2	240.1	262.2	248.3	277.7	289.9
	±SE	23.9	18.6	24.4	22.7	20.1	17.6	25.2	26.7	26.6
6	$\bar{X}$	386.3	376.5	424.7*	456.5	463.9	515.3	526.0	435.3	642.7
	±SE	52.0	57.4	67.1	68.6	71.7	70.3	69.8	71.5	77.2
Weight										
1	$\bar{X}$	164.4	163.9	197.5*	207.3	221.3	235.2	226.2	250.7	256.5
	±SE	15.4	12.6	16.5	20.1	17.9	18.1	19.2	19.9	24.4
3	$\bar{X}$	189.6	224.4*	256.3	254.0	252.4	274.4	275.2	295.6	303.0
	±SE	21.7	17.6	22.8	19.8	18.6	20.9	17.3	23.0	23.6
6	$\bar{X}$	376.5	356.1	408.4*	427.1	515.5	512.9	534.9	548.8	623.1
	±SE	45.2	35.5	44.2	34.6	34.6	48.2	52.7	49.9	56.1

Values are $\bar{X}$ ± SE.
IK denotes isokinetic device.
* Significantly greater than pretest value from this time on, $p<.05$.

Appendix A-4. 1 repetition maximum values (N) from the weight device in isokinetic and weight conditions across the training period.

	Time (weeks)								
	Pre	2	5	7	9	12	15	17.5	Post
IK	128.45	133.1	143.55	140.05	144.35	157.8	163.3	166.95	183.3
	11.3	10.25	13.25	12.15	14.75	14	14.55	14.65	13.75
	**	*	*	*	*	*	*	*	*
Weight	118.1	141.7	164.6	174.75	183.1	191.55	205.8	209.25	220.5
	9.5	12	15.25	12.55	16.85	17.2	15.1	15.3	15.1

Values are $\bar{X} \pm SE$.
** Isokinetic significantly greater than weight condition, $p<.05$.
* Weight significantly greater than isokinetic condition, $p<.05$.

Appendix A-5. Isometric dynamometer peak torque in isokinetic and weight conditions expressed as a percentage of the pretest value.

Joint Angle degrees	Time of Test: 7 weeks $\bar{X}$	SE	14 weeks $\bar{X}$	SE	Post $\bar{X}$	SE
IK						
75	103.6	7.0	110.3	8.5	115.4	5.5
90	101.7	5.5	110.7	6.4	111.1	8.1
105	100.7	6.4	109.3	5.5	112.7	5.3
120	107.2	6.8	110.6	5.9	111.4	3.9
135	107.4	7.1	114.8	7.2	109.0	6.4
150	101.1	6.4	107.6	6.6	103.9	6.2
165	106.4	9.5	109.9	9.9	121.9	9.7
Weight						
75	105.8	7.6	114.8	6.1	113.9	8.1
90	107.0	3.8	112.2	3.4	115.7	6.4
105	108.5	4.6	112.5	5.9	112.6	6.4
120	106.5	5.0	115.5	5.7	114.3	7.0
135	111.4	6.0	113.9	7.4	117.4	8.6
150	118.7	7.8	120.6	10.1	125.9	12.0
165	116.8	10.6	122.0	11.6	122.4	10.8

Values are $\bar{X} \pm$ SE.
Ik denotes isokinetic condition.

Appendix A-6. Isokinetic device MVC in isokinetic and weight conditions (% pretest) at 7 weeks, 14 weeks and post training.

Velocity		Pre	2	5	7	9	12	15	17.5	Post
					Time (weeks)					
IK										
1	X̄	100.0	102.2	120.9**	116.4	119.2	127.1	133.2	154.2	145.9
	+SE		9.5	11.9	10.8	13.9	11.2	11.7	12.0	13.1
3	X̄	100.0	114.1	131.6**	131.1	130.1	147.6	135.4	145.3	161.5
	+SE		10.2	16.4	12.1	10.9	13.9	12.4	21.4	18.1
6	X̄	100.0	99.7	113.9	122.7**	127.9	145.7	145.4	164.2	177.9
	+SE		5.9	7.8	8.5	10.4	10.0	6.9	14.9	12.8
Weight			*	*	*	*	*	*	*	*
1	X̄	100.0	109.2	134.4**	144.0	136.7	157.6	149.4	168.6	168.1
	+SE		8.4	10.9	13.9	9.1	10.7	8.2	10.0	9.2
3	X̄	100.0	137.0**	147.7	151.2	144.3	159.5	161.8	174.8	183.7
	+SE		22.1	10.9	12.2	12.2	11.3	14.0	17.3	18.0
6	X̄	100.0	101.0	117.5**	129.9	136.8	155.0	158.7	169.4	193.8
	+SE		7.2	8.9	11.2	14.6	13.3	11.6	21.0	21.7

Values are $\bar{X} \pm$ SE.

* Significantly greater increase in weight condition, $p<.05$.

** Significantly greater than pretest from this time on, $p<.05$.

Appendix A-7. Relative 1RM values for the weight device in isokinetic and weight conditions as a percentage of the pretest value.

		Time (weeks)								
		Pre	2	5	7	9	12	15	17.5	Post
IK	$\bar{X}$	100.0	108.8	114.2**	115.4	119.7	134.5	139.4	143.8	158.6
	±SE		9.9	10.0	12.7	14.5	16.6	21.1	24.6	25.6
			*	*	*	*	*	*	*	*
Weight	$\bar{X}$	100.0	123.3**	142.2	155.2	160.4	178.5	184.9	189.7	202.9
	±SE		17.6	17.3	15.0	16.2	14.8	18.8	24.1	19.0

Values are $\bar{X}$ ± SE.
* Weight significantly greater than isokinetic condition, $p<.05$.
** Significantly greater than pretest from this time on, $p<.05$.

Appendix A-8. Bicep, brachialis and total flexor cross sectional area (cm^2, % pretest) in isokinetic and weight conditions.

	Absolute Area (cm^2)				Relative Increase (% pretest value)	
	Pre		Post			
Biceps	$\bar{X}$	SE	$\bar{X}$	SE	$\bar{X}$	SE
IK	11.1	0.6	12.2	0.7 *	111.2	4.3
Weight	11.9	0.8	12.7	0.8 *	108.7	4.6
Brachialis						
IK	6.1	0.5	7.9	0.8 *	133.9	9.3
Weight	5.7	0.4	** 8.3	0.8 *	** 150.0	8.9
Total Flexor						
IK	17.2	1.1	20.1	1.5 *	118.9	4.5
Weight	17.6	1.1	21.1	1.4 *	122.0	4.9

Values are $\bar{X} \pm$ SE.
* Significant increase, pre to post training, $p<.05$.
** Significantly greater increase in weight trained condition, $p<.05$.

Appendix A-9. Type I, Type II fibre areas and Type II:Type I fibre area ratios in isokinetic and weight conditions pre and post training.

	Absolute Area (μm^2) Pre		Post		Relative Change (% pretest value)		Type II:Type I area ratio	
Type I	$\bar{X}$	SE	$\bar{X}$	SE	$\bar{X}$	SE	Pre	Post
IK	4240.7	563.9	4274.0	447.3	102.4	8.3	1.31 ±.1	1.47** ±.1
Weight	3927.9	496.3	4116.4	238.2	112.9	14.7	1.32 ±.1	1.44** ±.1
Type II	*		*					
IK	5530.3	528.7	6235.9	346.0	118.6	14.9		
Weight	5174.0	534.4	6070.5	292.6	123.0	14.7		

Values are $\bar{X}$ ± SE.
* Type II fibres significantly larger than Type I fibres, $p<.05$.
** Significantly greater than pretraining, $p<.057$.

Appendix A-10. Twitch peak torque in isokinetic and weight conditions, pre to post training from 75 to 165° elbow flexion (180° = full extension).

Time		Joint Position (°flexion)						
IK		75	90	105	120	135	150	165
Pre	$\bar{X}$	1.78	3.86	5.01	5.66	6.35	6.81	7.48
	±SE	0.17	0.29	0.36	0.30	0.39	0.43	0.48
Week 7	$\bar{X}$	2.62	4.54	5.48	6.38	6.37	6.77	7.19
	±SE	0.45	0.56	0.51	0.53	0.69	0.71	0.75
Week 14	$\bar{X}$	3.27*	5.01*	6.38*	7.13*	7.38*	8.08*	8.01
	±SE	0.45	0.52	0.47	0.53	0.56	0.54	0.48
Post	$\bar{X}$	3.15*	4.82*	5.79	6.69	6.98	7.26	6.96
	±SE	0.43	0.50	0.57	0.67	0.70	0.75	0.65
Weight								
Pre	$\bar{X}$	2.20	4.02	5.49	6.20	6.97	7.08	7.60
	±SE	0.41	0.51	0.65	0.65	0.72	0.68	0.77
Week 7	$\bar{X}$	2.44	4.22	5.52	6.45	6.72	7.13	6.97
	±SE	0.42	0.43	0.34	0.36	0.53	0.51	0.60
Week 14	$\bar{X}$	3.42*	4.92*	6.38	7.29*	7.80	8.02*	8.17
	±SE	0.38	0.43	0.52	0.43	0.51	0.60	0.86
Post	$\bar{X}$	2.82	4.87	6.23	6.85	7.36	7.49	7.59
	±SE	0.46	0.54	0.62	0.70	0.76	0.78	0.83

Values are $\bar{X}$ ± SE.
* Significant increase over pre training value, $p<.05$.
IK denotes isokinetic condition.

Appendix A-11. Relative twitch peak torque values in isokinetic and weight conditions, pre to post training from 75 to 165° elbow flexion.

Time		Joint Position (°flexion)						
IK		75	90	105	120	135	150	165
Pre	X̄	100.0	100.0	100.0	100.0	100.0	100.0	100.0
Week 7	X̄	152.9*	129.7*	114.9	114.9	103.3	101.0	106.8
	±SE	27.3	20.4	15.6	10.8	10.9	11.5	13.5
Week 14	X̄	195.2*	139.5*	135.6*	129.4*	123.2	124.3	113.0
	±SE	30.3	17.5	15.1	11.6	12.4	9.9	8.2
Post	X̄	182.0*	129.3*	108.8	119.4	115.2	109.3	102.4
	±SE	21.9	15.5	16.8	9.4	12.2	9.2	8.8
Pre	X̄	100.0	100.0	100.0	100.0	100.0	100.0	100.0
Week 7	X̄	144.5*	113.7	116.9	111.1	102.5	104.3	94.6
	±SE	38.6	13.8	17.6	10.8	11.0	8.9	6.2
Week 14	X̄	209.5*	135.7*	139.6*	131.6*	124.1	124.7	116.7
	±SE	60.6	17.1	22.5	16.8	13.2	12.4	9.2
Post	X̄	172.1*	130.0*	132.6*	123.0	116.0	113.1	106.4
	±SE	56.8	17.4	21.4	16.6	13.1	10.7	11.1

Values are X̄ ± SE.

* Significant increase from pretraining, $p<.05$.

IK denotes isokinetic condition.

Appendix A-12. Time to peak torque in weight and isokinetic conditions pre to post training from 75 to 165° elbow flexion (180° = full extension).

Isokinetic Time		Joint Position (°flexion) 75	90	105	120	135	150	165
Pre	$\bar{X}$	55.0	63.2	66.0	65.7	58.7	50.3	53.0
	±SE	4.6	2.7	2.9	3.3	2.6	1.9	2.0
Week 7	$\bar{X}$	62.2	68.7	63.8	58.0	55.2	52.5	55.7
	±SE	7.1	2.6	2.3	2.4	2.2	3.0	2.7
Week 14	$\bar{X}$	64.3	66.5	60.2	51.3	54.3	55.5	55.3
	±SE	1.9	1.0	3.1	2.5	1.8	2.2	1.7
Post	$\bar{X}$	69.5*	71.2	65.5	60.2	53.7	51.8	53.2
	±SE	4.2	2.4	3.5	2.1	1.8	1.6	1.4
Weight								
Pre	$\bar{X}$	61.3	63.7	65.5	59.0	56.2	53.5	53.0
	±SE	2.5	2.9	3.4	2.5	2.7	2.9	1.7
Week 7	$\bar{X}$	61.2	61.8	64.0	59.8	56.2	56.3	57.2
	±SE	3.6	3.6	3.4	2.8	3.1	2.7	1.9
Week 14	$\bar{X}$	64.0	65.7	55.2	58.0	51.2	51.5	55.8
	±SE	4.5	4.6	3.0	2.3	2.1	2.1	2.2
Post	$\bar{X}$	63.2	68.3	63.5	59.2	54.8	53.2	54.3
	±SE	6.2	4.6	5.4	4.7	4.7	2.8	3.0

Values are $\bar{X}$ ± SE.
* Significant increase from pretraining, $p<.05$.

Appendix A-13. 1/2 relaxation time in isokinetic vs weight trained conditions from 75 to 165° elbow flexion (180° = full extension).

Time		Joint Position (°flexion)						
IK		75	90	105	120	135	150	165
Pre	$\bar{X}$	60.8	65.7	69.3	83.0	82.8	94.0	86.0
	±SE	6.2	5.8	9.0	8.9	9.8	10.6	9.3
Week 7	$\bar{X}$	64.7	57.5	68.5	73.3	80.5	93.0	95.8
	±SE	11.9	5.1	6.2	7.1	8.7	9.4	7.4
Week 14	$\bar{X}$	55.2	59.0	64.2	72.2	75.3	70.3*	75.7*
	±SE	5.9	5.6	5.7	8.3	7.3	10.9	7.1
Post	$\bar{X}$	57.7	57.0	63.2	71.2	82.3	83.7	85.8
	±SE	7.7	5.7	6.8	3.9	8.0	6.0	6.0
Weight								
Pre	$\bar{X}$	60.7	71.0	77.4	85.3	94.8	92.2	85.3
	±SE	7.6	10.5	7.5	9.8	11.8	11.5	10.5
Week 7	$\bar{X}$	62.5	73.3	78.3	87.0	91.5	93.2	95.3
	±SE	6.9	10.6	9.3	9.7	11.4	7.8	7.6
Week 14	$\bar{X}$	57.7	61.7	75.3	75.5	84.2	79.3*	74.3*
	±SE	5.5	8.6	10.8	9.3	6.1	7.5	7.8
Post	$\bar{X}$	61.2	62.7	68.7	83.3	93.3	89.8	93.2
	±SE	7.3	8.9	8.7	8.9	9.6	5.8	5.8

Values are X + SE.
* Significant decrease from pretraining, $p<.05$.

Appendix A-14. Maximum rate of torque development in isokinetic and weight conditions from 75 to 165° elbow flexion (180° = full extension).

Time		Joint Position (°flexion)						
IK		75	90	105	120	135	150	165
Pre	X̄	53.8	122.9	151.7	163.1	183.8	219.8	228.3
	±SE	8.5	18.3	18.1	8.3	21.1	30.1	30.4
Week 7	X̄	89.3*	126.1	163.4	218.3	224.3	246.7	235.6
	±SE	18.2	18.6	16.2	34.0	36.2	36.8	44.1
Week 14	X̄	111.7*	167.2*	224.2*	286.6*	306.7*	310.5*	313.6*
	±SE	18.0	18.4	22.2	21.8	33.4	34.8	30.3
Post	X̄	97.4*	146.6	182.6*	204.9*	206.4	213.4	204.1
	±SE	15.6	18.5	18.3	20.7	24.9	21.5	22.3
Weight								
Pre	X̄	71.3	125.1	184.6	196.4	217.1	213.9	207.6
	±SE	11.2	13.0	9.7	15.6	25.0	16.3	16.8
Week 7	X̄	77.8	135.8	172.6	206.3	217.3	243.5	232.7
	±SE	12.7	15.7	11.4	28.4	29.5	23.9	18.3
Week 14	X̄	105.0*	144.9*	196.9*	246.6*	263.7*	277.4*	291.2*
	±SE	13.1	5.0	13.6	23.5	21.4	18.6	33.5
Post	X̄	84.0	139.6	191.0	204.9	211.0	214.8	218.7
	±SE	11.4	15.7	13.2	17.2	19.3	22.9	25.2

Values are X̄ ± SE.
* Significant increase from pretraining, $p<.05$.
IK denotes isokinetic condition.

Appendix A-15. Maximum rate of torque relaxation in isokinetic and weight conditions from 75 to 165° elbow flexion (180° = full extension).

Time		Joint Position (°flexion) 75	90	105	120	135	150	165
IK								
Pre	$\bar{X}$	25.0	53.1	68.3	67.5	70.5	89.7	96.3
	±SE	3.7	9.4	8.5	8.2	10.0	14.7	20.5
Week 7	$\bar{X}$	44.7*	67.0	72.4	84.0	111.0	77.8	77.8
	±SE	7.8	11.5	11.9	12.3	19.8	10.4	9.7
Week 14	$\bar{X}$	50.9*	80.9*	89.4*	106.3*	99.4*	138.9*	131.7*
	±SE	7.5	8.4	9.7	10.9	9.3	18.7	19.2
Post	$\bar{X}$	60.6*	81.3*	84.6	85.2	78.3	88.2	81.3
	±SE	10.8	10.1	7.3	9.5	7.8	9.3	10.6
Weight								
Pre	$\bar{X}$	37.9	55.4	71.3	66.7	80.4	85.7	83.5
	±SE	7.5	7.6	11.2	7.9	10.2	15.2	9.5
Week 7	$\bar{X}$	37.8	59.3	79.4	78.6	78.6	82.4	80.1
	±SE	7.0	7.7	8.7	7.3	9.0	10.0	12.2
Week 14	$\bar{X}$	58.6*	77.8*	92.5*	104.8*	110.2*	117.9*	114.8*
	±SE	7.5	9.4	13.1	16.2	15.9	14.8	12.0
Post	$\bar{X}$	52.2	76.7*	96.6*	85.2*	80.6	106.6	82.8
	±SE	9.0	9.9	16.9	11.0	7.7	26.4	11.7

Values are $\bar{X}$ ± SE.
* Significantly greater than pretraining value, $p<.05$.
IK denotes isokinetic condition.

Appendix B, 1-15. Tabled data for males vs females.

Appendix B-1. Cybex peak torque (N.m) at pre, 7 weeks and post training in males and females.

Velocity (°/s)	Pre $\bar{X}$	SE	7 weeks $\bar{X}$	SE	Post $\bar{X}$	SE
Males						
30	64.1	5.3	56.8	4.6	67.9	4.6
120	52.1	4.2	45.6	3.2	51.1	3.1
180	45.8	4.9	41.5	2.8	45.1	2.7
240	48.4	4.1	41.5	2.7	41.1**	3.3
Females						
30	29.9	1.6	31.3	2.2	35.3*	2.2
120	23.3	1.7	29.0	2.0	28.7*	2.3
180	23.3	2.5	23.1	2.3	25.1	2.2
240	23.6	2.7	23.6	1.7	25.0	1.9

Values are $\bar{X} \pm$ SE.
** Significant decrease from pretest, $p<.05$.
* Significant increase from pretest, $p<.05$.
Male values significantly greater than females at all times.

App. B-2. Isometric dynamometer peak torque (N.m) in males and females from 75 to 165° elbow flexion (180° = full extension).

Joint Angle degrees	Pre		Time of Test 7 weeks		14 weeks		Post		% Change
	$\bar{X}$	SE	$\bar{X}$	SE	$\bar{X}$	SE	$\bar{X}$	SE	
Males									
75	57.6	6.3	58.9	7.7	61.7	6.4	65.3*	6.2	14.9
90	67.0	7.9	65.6	7.5	71.5	7.3	72.2*	7.4	9.9
105	71.3	8.4	69.4	8.3	75.1	7.9	76.1*	9.1	7.8
120	72.0	8.4	71.5	7.7	73.3	5.4	74.9	9.0	4.7
135	69.7	7.8	68.7	6.4	69.4	6.5	70.4	8.0	1.6
150	65.8	7.0	61.9	6.4	63.9	6.2	64.7	6.5	3.8
165	56.5	7.1	51.4	5.6	56.3	4.9	56.8	6.3	5.9
Females									
75	33.6	3.7	34.7	2.2	38.0	2.7	37.4*	2.3	14.4
90	34.5	3.9	37.1	2.5	38.8	2.9	39.4*	2.0	17.0
105	35.0	4.0	37.8	2.4	39.4	3.4	40.1*	2.5	17.5
120	33.6	4.1	37.1	3.6	39.2	3.5	39.6*	3.2	21.0
135	30.0	4.0	34.8	3.7	35.1	3.1	36.3*	3.4	24.9
150	25.9	4.2	30.9	4.1	31.4	3.0	31.3*	3.7	26.0
165	20.8	3.8	24.4	3.1	25.0	3.4	27.1*	3.2	38.4

Values are $\bar{X} \pm$ SE.
* Significant increase from pre to post training, $p<.05$.

App. B-3. Isokinetic device MVC (N) in males and females at 3 velocities from pre to post training (1-fastest,6-slowest).

Velocity		Pre	2	5	7	9	12	15	17.5	Post
					Time (weeks)					
Males										
1	$\bar{X}$	251.9	232.8	264.6*	263.8	291.6	304.6	293.2	332.4	339.8
	±SE	22.9	20.5	21.8	25.5	20.8	23.9	27.5	26.1	38.8
3	$\bar{X}$	276.5	302.3*	335.7	327.5	343.9	361.0	353.6	383.0	393.7
	±SE	25.7	23.3	28.5	27.1	23.9	24.9	30.7	33.4	32.4
6	$\bar{X}$	542.3	501.5	558.6*	561.9	619.9	649.3	688.5	726.0	808.5
	±SE	65.5	67.5	74.4	70.3	70.5	78.9	78.6	73.9	85.5
Females										
1	$\bar{X}$	87.8	102.3*	125.5	131.8	123.3	141.3	143.8	160.9	153.6
	±SE	9.1	13.5	10.0	15.6	15.4	13.7	19.3	18.8	14.1
3	$\bar{X}$	109.5	135.2*	157.5	161.7	148.6	175.6	169.9	190.3	199.3
	±SE	20.0	12.9	18.7	15.4	14.9	13.6	11.8	16.3	17.9
6	$\bar{X}$	220.5	231.2	274.4*	321.8	359.6	379.0	372.4	258.1	457.3
	±SE	31.7	25.4	36.9	32.9	35.8	39.6	43.9	47.5	47.8

Values are $\bar{X} \pm$ SE.
Male values are significantly greater than females at all times.
* Significantly greater than pretest from this time on, $p<.05$.

Appendix B-4. 1 repetition maximum values (N) from the weight device in males and females across the training period.

	Time (weeks)								
	Pre	2	5	7	9	12	15	17.5	Post
Males	183.25	197.55*	221.15	219.05	228.65	238.1	251.55	255.6	270.7
	15.05	14.95	18.45	14.3	22	23.3	20.7	20.05	20.7
Females	63.3	77.25*	87	95.75	98.8	111.25	117.55	120.6	133.1
	5.75	7.3	10.05	10.4	9.6	7.9	8.95	9.9	8.15

Values are $\bar{X} \pm$ SE.
Males values are significantly greater than females at all times.
* Significantly greater than pretest from this time on, $p<.05$.

Appendix B-5. Isometric dynamometer peak torque in males and females expressed as a percentage of the pretest value.

Joint Angle degrees	Time of Test: 7 weeks $\bar{X}$	SE	14 weeks $\bar{X}$	SE	Post $\bar{X}$	SE	
Males							
75	102.6	6.1	108.8	6.1	114.9	6.5	
90	99.0	4.9	108.6	5.0	109.9	5.6	
105	98.1	4.7	107.2	5.7	107.8	6.0	
120	101.1	5.8	107.1	5.5	104.7	4.4	
135	101.1	7.9	107.4	6.3	101.6	5.8	
150	95.7	6.2	98.6	6.3	103.8	8.5	
165	98.7	9.6	104.3	10.4	105.9	7.8	
Females							
75	106.7	8.5	116.3	8.5	114.4	7.1	
90	109.7	4.4	114.3	4.8	117.0	8.9	*
105	111.0	6.3	114.6	5.7	117.5	5.7	*
120	112.6	6.0	119.0	6.1	121.0	6.6	*
135	117.7	5.3	121.3	8.3	124.9	9.1	*
150	124.1	8.0	129.6	10.4	126.0	9.8	*
165	124.5	10.6	127.6	11.0	138.4	12.7	*

Values are $\bar{X} \pm$ SE.
* Significant increase from pre training, $p<.05$.

Appendix B-6. Isokinetic device MVC in males and females expressed as a percentage of the pretest value at 7 weeks, 14 weeks and post training.

			Time (weeks)							
Velocity		Pre	2	5	7	9	12	15	17.5	Post
Males										
1	$\bar{X}$	100.0	94.1	108.4	105.5	112.6**	122.2	117.4	134.0	134.4
	±SE		9.2	12.1	7.5	8.5	9.4	8.2	9.6	8.0
3	$\bar{X}$	100.0	112.5**	125.0	121.6	128.8	133.5	129.9	130.9	146.0
	±SE		9.6	12.2	8.0	10.7	10.3	12.2	17.9	12.4
6	$\bar{X}$	100.0	92.0	102.8	104.4	117.4**	120.8	128.5	139.1	152.5
	±SE		4.8	4.6	6.4	8.7	6.0	6.6	13.5	11.8
			*	*	*	*	*	*	*	*
Females										
1	$\bar{X}$	100.0	117.3**	146.9	154.9	143.3	162.5	165.2	188.7	179.6
	±SE		8.7	10.7	17.2	14.5	12.5	11.6	12.4	14.3
3	$\bar{X}$	100.0	138.7**	154.3	160.7	145.6	173.6	167.2	189.1	199.2
	±SE		22.6	15.1	16.4	12.5	14.9	14.3	20.8	23.8
6	$\bar{X}$	100.0	108.7	128.6**	148.2	147.3	179.9	175.6	194.5	219.2
	±SE		8.4	12.1	13.3	16.4	17.4	11.9	22.3	22.7

Values are $\bar{X}$ ± SE.
* Female values significantly greater than males, $p<.05$.
** Significantly greater than pretest from this time on, $p<.05$.

Appendix B-7. Relative 1RM values for the weight device in males and females expressed as a percentage of the pretest value.

		Time (weeks)								
		Pre	2	5	7	9	12	15	17.5	Post
Males	$\bar{X}$	100.0	105.6	118.0**	118.0	121.8	132.6	134.8	137.0	145.5
	±SE		6.1	9.1	12.2	12.9	11.8	13.2	15.0	18.1
			*	*	*	*	*	*	*	*
Females	$\bar{X}$	100.0	126.6**	138.4	152.5	158.3	180.4	189.5	196.5	216.0
	±SE		21.5	18.2	15.5	17.7	19.6	26.7	33.7	26.5

Values are $\bar{X} \pm$ SE.
* Female values significantly greater than males, $p<.05$.
** Significantly greater than pretest from this time on, $p<.05$.

Appendix B-8. Bicep, brachialis, and total flexor cross sectional area (cm^2, % pretest) in males and females pre and post training.

	Absolute Area (cm^2)					Relative Increase (% pretest value)	
	Pre		Post				
	$\bar{X}$	SE	$\bar{X}$	SE		$\bar{X}$	SE
Biceps							
Males	15.4	1.1	16.4	1.2	*	107.2	4.5
Females	7.6	0.3	8.5	0.4	*	112.7	4.4
Brachialis							
Males	7.7	0.6	10.0	0.9	*	131.4	11.6
Females	4.1	0.3	6.2	0.7	*	152.5	6.7
Total Flexor							
Males	23.1	1.6	26.4	1.9	*	114.8	5.8
Females	11.6	0.6	14.7	1.0	*	126.1	3.6

Values are $\bar{X} \pm$ SE.
* Significant increase from pretraining, $p<.05$.
Male areas were significantly greater than females at all times, $p<.001$.

Appendix B-9. Type I and Type II fibre areas and Type II:Type I fibre area ratios, in males and females pre and post training.

	Absolute Area (µm2) Pre		Post		Relative Change (% pretest value)		Type II:Type I area ratio	
Type I	X	SE	X	SE	X	SE	Pre	Post
Males	4582.4 *	592.6	5100.8 *	498.8	116.35	11.2	1.61 ±.1	1.66 ±.2 **
Females	3586.15	467.5	3289.6	186.7	98.85	11.9	1.01 ±.1	1.25 ±.1
Type II								
Males	7134.1 *	627.9	8187.5 *	316.9	121	16.4		
Females	3570.3	358.7	4118.9	321.7	120.6	13.2		

Values are $\bar{X} \pm$ SE.
* Male values significantly greater than females, $p<.05$.
** Significant overall increase from pretraining, $p<.057$.

Appendix B-10. Twitch peak torque (N.m) in males and females, pre to post training from 75 to 165° elbow flexion (180° = full extension).

Males		Joint Position (°flexion)						
Time		75	90	105	120	135	150	165
Pre	$\bar{X}$	2.50	5.37	7.57	8.64	9.92	10.36	11.29
	±SE	0.40	0.58	0.69	0.66	0.75	0.72	0.81
Week 7	$\bar{X}$	3.21	5.98	7.88	9.41	9.68	10.52	10.76
	±SE	0.62	0.73	0.68	0.65	0.98	0.99	1.10
Week 14	$\bar{X}$	4.10*	6.40*	8.70*	10.25*	10.91*	11.55*	11.74
	±SE	0.59	0.73	0.78	0.71	0.84	0.92	1.16
Post	$\bar{X}$	3.94*	6.39*	8.35	9.59	10.29	10.73	10.53
	±SE	0.67	0.75	0.91	1.05	1.14	1.26	1.24
Females								
Pre	$\bar{X}$	1.47	2.52	2.93	3.22	3.40	3.54	3.80
	±SE	0.18	0.22	0.32	0.30	0.36	0.39	0.44
Week 7	$\bar{X}$	1.85	2.78	3.13	3.41	3.41	3.39	3.40
	±SE	0.26	0.26	0.17	0.24	0.24	0.23	0.25
Week 14	$\bar{X}$	2.59*	3.53*	4.06*	4.16*	4.28*	4.55*	4.44
	±SE	0.24	0.22	0.22	0.25	0.24	0.22	0.18
Post	$\bar{X}$	2.03	3.30	3.68	3.95	4.05	4.02	4.02
	±SE	0.22	0.30	0.28	0.33	0.31	0.27	0.24

Values are $\bar{X}$ ± SE.
Male values significantly greater than females at all times.
* Significant increase from pretraining, $p<.05$.

Appendix B-11. Relative twitch peak torque values (% pretest) for males and females pre to post training from 75 to 165° elbow flexion.

Males		Joint Position (°flexion)						
Time		75	90	105	120	135	150	165
Pre	$\bar{X}$	100	100	100	100	100	100	100
Week 7	$\bar{X}$	150.2*	129.4*	112.3	113.6	100.4	103.8	96.5
	±SE	22.6	20.9	14.0	10.6	10.5	9.4	6.3
Week 14	$\bar{X}$	207.9*	127.0*	120.9	123.2	113.2	113.6	105.6
	±SE	48.8	14.5	10.2	10.1	7.7	5.9	5.3
Post	$\bar{X}$	196.8*	123.0	102.9	113.2	104.8	102.3	96.9
	±SE	41.5	16.1	14.4	9.2	8.3	5.3	7.1
Pre	$\bar{X}$	100	100	100	100	100	100	100
Week 7	$\bar{X}$	147.3*	114.0	119.6	112.3	105.4	101.5	104.9
	±SE	43.4	13.2	19.1	11.0	11.5	11.0	13.5
Week 14	$\bar{X}$	196.9*	148.3*	154.4*	137.8*	134.1*	135.4*	124.1
	±SE	42.1	20.1	27.4	18.3	18.0	16.5	12.1
Post	$\bar{X}$	157.3*	136.2*	138.5*	129.3*	126.5	120.1	111.9
	±SE	37.2	16.8	23.8	16.9	17.0	14.6	12.7

Values are $\bar{X}$ ± SE.

* Significant increase from pretraining, p<.05.

Appendix B-12. Time to peak torque in males and females, pre to post training from 75 to 165° elbow flexion (180°= full extension).

	Joint Position (°flexion)							
Males								
Time		75	90	105	120	135	150	165
Pre	$\bar{X}$	58.8	68.0	68.5	68.5	61.3	55.3	56.2
	±SE	5.8	4.6	5.0	4.6	4.4	4.1	3.0
Week 7	$\bar{X}$	63.5	64.8	62.7	60.2	57.8	58.0	57.8
	±SE	6.1	4.6	4.8	4.2	4.1	4.1	2.9
Week 14	$\bar{X}$	63.3	64.8	56.0	51.5	55.8	56.7	59.7
	±SE	4.5	4.1	4.7	2.8	2.9	3.2	3.0
Post	$\bar{X}$	67.7*	73.2	68.5	63.3	55.5	55.3	56.0
	±SE	6.6	5.2	6.8	5.1	4.0	2.3	2.7
Females								
Pre	$\bar{X}$	57.5	58.8	63.0	56.2	53.5	48.5	49.8
	±SE	1.3	1.1	1.3	1.3	0.9	0.7	0.7
Week 7	$\bar{X}$	59.8	65.7	65.2	57.7	53.5	50.8	55.0
	±SE	4.7	1.6	0.9	1.0	1.2	1.6	1.7
Week 14	$\bar{X}$	65.0	67.3	59.3	57.8	49.7	50.3	51.5
	±SE	1.9	1.5	1.4	2.0	1.0	1.1	0.9
Post	$\bar{X}$	65.0*	66.3	60.5	56.0	53.0	49.7	51.5
	±SE	3.7	1.8	2.1	1.7	2.5	2.1	1.8

Values are $\bar{X}$ ± SE.
Significant overall decrease occurred from 75 to 165 .
* Significant increase (males and females combined) from pretraining, $p<.05$.

Appendix B-13. 1/2 relaxation time in males and females over the training period at 75 to 165° elbow flexion (180° = full extension).

Males		Joint Position (°flexion)						
Time		75	90	105	120	135	150	165
Pre	$\bar{X}$	51.7	54.8	61.8	70.2	75.3	87.8	86.2
	±SE	6.6	6.3	9.2	5.7	9.2	11.1	9.9
Week 7	$\bar{X}$	51.3	54.2	64.3	69.8	71.2	79.8	84.2
	±SE	6.9	5.5	6.5	7.1	9.7	9.4	6.5
Week 14	$\bar{X}$	47.5*	54.0	62.5	66.8	71.8	72.0	71.2
	±SE	5.7	6.3	6.6	7.8	6.7	7.3	7.6
Post	$\bar{X}$	48.2	52.0	56.0	66.7	79.8	83.2	84.5
	±SE	6.3	8.6	7.2	6.8	7.8	6.0	5.2
Females								
Pre	$\bar{X}$	69.8	81.8	84.9	98.2	102.3	98.3	85.2
	±SE	7.2	10.1	7.4	13.1	12.4	11.0	10.0
Week 7	$\bar{X}$	75.8	76.7	82.5	90.5	100.8	106.3	107.0
	±SE	11.8	10.2	9.0	9.7	10.3	7.8	8.4
Week 14	$\bar{X}$	65.3*	66.7	77.0	80.8	87.7	77.7	78.8
	±SE	5.6	7.9	9.9	9.8	6.7	11.1	7.3
Post	$\bar{X}$	70.7	67.7	75.8	87.8	95.8	90.3	94.5
	±SE	8.7	6.0	8.3	6.0	9.9	5.8	6.6

Values are $\bar{X}$ ± SE.
* 14 week overall values significantly less than pre training, $p<.05$.
Female values significantly greater than males overall.

Appendix B-14. Maximum rate of torque development in males and females from 75 to 165° elbow flexion (180° = full extension).

Males		Joint Position (°flexion)						
Time		75	90	105	120	135	150	165
Pre	$\bar{X}$	78.1	163.8	236.6	242.7	286.6	302.5	314.7
	±SE	15.2	24.9	19.2	14.6	35.1	29.4	33.1
Week 7	$\bar{X}$	106.3	181.3	245.8	312.6*	340.3*	385.3*	363.1*
	±SE	20.6	26.3	18.4	43.0	54.3	51.0	50.0
Week 14	$\bar{X}$	124.8*	193.4*	278.2*	379.1*	419.2*	416.1*	436.9*
	±SE	18.7	12.9	25.2	30.5	42.8	31.2	42.8
Post	$\bar{X}$	118.2*	179.5	252.4	284.6*	293.9	297.6	287.7
	±SE	20.5	23.0	21.7	30.5	38.0	35.9	35.3
Females								
Pre	$\bar{X}$	47.0	84.2	99.7	116.8	114.3	131.2	121.1
	±SE	4.5	6.5	8.6	9.3	11.0	17.0	14.2
Week 7	$\bar{X}$	60.7	80.6	90.2	112.0	101.3	104.9	105.2
	±SE	10.3	7.9	9.3	19.3	11.4	9.7	12.4
Week 14	$\bar{X}$	91.9*	118.7*	142.9*	154.1*	151.2*	171.8*	167.9*
	±SE	12.3	10.5	10.6	14.8	12.0	22.2	21.1
Post	$\bar{X}$	63.2	106.7	121.2	125.1	123.5	130.6	135.0
	±SE	6.5	11.1	9.8	7.5	6.2	8.5	12.2

Values are $\bar{X}$ ± SE.
* Significantly greater than pre training, $p<.05$.
Male values significantly greater than females at all times.

Appendix B-15. Maximum rate of torque relaxation (N.m/s) in males and females at 75 to 165° elbow flexion (180° = full extension).

Males		Joint Position (°flexion)						
Time		75	90	105	120	135	150	165
Pre	$\bar{X}$	40.2	78.1	103.9	101.6	113.0	127.6	122.2
	±SE	8.7	14.8	15.9	12.2	13.5	17.6	16.6
Week 7	$\bar{X}$	56.2	90.9	115.6	125.6*	151.8*	123.3	122.5
	±SE	10.3	14.2	15.6	15.7	21.9	16.5	17.1
Week 14	$\bar{X}$	70.9*	108.6*	133.3*	158.0*	156.4*	181.3*	175.7*
	±SE	9.7	13.8	16.7	19.8	17.5	20.3	20.4
Post	$\bar{X}$	79.0*	114.3*	135.8*	125.8*	115.1	142.7	118.9
	±SE	14.7	13.7	19.0	16.6	11.7	27.2	14.8
Females								
Pre	$\bar{X}$	22.8	30.3	35.6	32.6	37.9	47.8	57.6
	±SE	2.5	2.2	3.8	3.9	6.8	12.3	13.4
Week 7	$\bar{X}$	26.2	35.4	36.2	37.0	37.7	37.0	35.4
	±SE	4.5	5.0	4.9	3.9	6.9	3.9	4.9
Week 14	$\bar{X}$	38.5	50.1*	48.5	53.2*	53.2	75.5*	70.9
	±SE	5.3	4.0	6.1	7.3	7.7	13.2	10.8
Post	$\bar{X}$	33.7	43.7	45.4	44.5	43.7	52.2	45.2
	±SE	5.1	6.3	5.3	4.0	3.8	8.5	7.5

Values are $\bar{X}$ ± SE.
* Significantly greater than pre training, $p<.05$.
Male values are significantly greater than females at all times, $p<.05$.