POSITIVE ADAPTATIONS TO
WEIGHT-LIFTING TRAINING IN THE ELDERLY

POSITIVE ADAPTATIONS TO WEIGHT-LIFTING TRAINING IN THE ELDERLY

BY

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ABSTRACT

Maximal weight-lifting performance, isometric strength, isokinetic torque, whole muscle and individual fibre cross-sectional areas, and muscle evoked contractile properties were assessed in 14 elderly males before and after 12 weeks of weight-lifting training. Dynamic elbow flexion training of one arm resulted in a significant 48% mean increase in the maximal load that could be lifted once (1 RM) and a smaller improvement in isokinetic torque (8.8%) but no change in isometric strength. In the contralateral control arm, 1 RM and isokinetic torque increased by 12.7 and 6.5 %, respectively, but isometric strength did not change. The interpolated twitch technique confirmed complete motor unit activation during a maximal isometric contraction of the elbow flexors before and after training. Bilateral leg press training effected mean increases of 17 and 23% in isokinetic torque and dynamic lifting capacity, respectively. The mean maximal cross-sectional area of the elbow flexors (biceps brachii and brachialis) increased by 17.4% in the trained arm but did not change in the control arm. The increase in the mean area of the Type II fibres in the biceps brachii muscle in the trained arm (30.2%) was greater than the corresponding change in the control arm (10.7%, $P < 0.05$). The most significant change in the the evoked contractile properties of the trained elbow flexors was the increase in twitch half-relaxation time. It is concluded that older individuals retain the potential for significant increases in strength performance and upper limb muscle hypertrophy in response to overload training.

TO MY MOTHER AND FATHER,

WHO TAUGHT THEIR SON TO OPEN WIDE HIS EYES AND WONDER.

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A very special thank you to:

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And finally to Digby Sale, who sat me down on a slice of the Canadian Shield one afternoon and told me what life was all about.

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1.0. BACKGROUND AND GENERAL OVERVIEW

1.1. ADAPTATIONS TO RESISTANCE TRAINING IN YOUNG ADULT MUSCLE

1.1.1. INCREASED VOLUNTARY STRENGTH

Although investigations into strength training had begun as early as the late 19th century, (Lombard,1892), it was not until Delorme (1945) undertook an investigation of the possible therapeutic applications that the scientific formalizations of weight training was initiated. Using a technique whereby the weight a subject trained with was increased as he/she adapted to the load (called "progressive resistance exercise") DeLorme found that exercising with a small number of repetitions and a heavy weight effected large gains in strength, whereas performing more repetitions with a lighter load enhanced muscular endurance. Since then, many investigators have reported that resistance training in young subjects increases strength of the upper and lower limbs, (Atha, 1981; McDonagh & Davies, 1983; Jones et al., 1989).

Individual responses to training are influenced by many factors including: the subject's age; level of training; genetic potential; the muscle being trained; and the type, frequency and duration of the training. Isometric strength has been shown to increase from 0.5 to 2% per day in response to isometric resistance training (McDonaugh & Davies, 1984), whereas most short-term weightlifting studies of 8 to 12 weeks duration have demonstrated gains of 25 to 30% in the maximum weight that could be lifted once (1RM) (Wilmore, 1974; Thorstenson et al., 1976, Wilmore et al., 1978; Jones et al.,1989).

1.1.2. INCREASED MUSCLE MASS

Increases in strength which result from resistance training may often be attributed in part to increases in muscle mass. When limb girth measurements have been used to reflect gains in muscle mass after training, increases have been documented in both the upper and lower limbs, (Wilmore, 1974; MacDougall et al., 1977; Wilmore et al., 1978; Moritani & de Vries, 1979; Hakkinen et al., 1985). The theory behind this technique is that muscle cross-sectional area can be estimated by correcting the overall limb girth measurements for skinfold thickness and subcutaneous fat deposits. Although the absolute magnitude of muscle cross-sectional area may only be approximated using this technique, relative changes brought about by training should be measurable by a skilled investigator.

Another indirect method that has been used to determine increases in muscle mass is to measure body weight and body fat. Increases in body weight with concurrent decreases in overall body fat, results in an increased total lean body mass, most likely because of gains in muscle mass, (Wilmore,1974; Brown & Wilmore, 1974; Wilmore et al., 1978).

The development of computerized axial tomography (CAT) and ultrasound techniques have enabled researchers to make more accurate measurements of the cross-sectional area of individual muscles. Studies have compared cross-sectional areas of muscles from subjects with dissimilar training backgrounds, (Schantz et al., 1983; Sale et al., 1987). Sale et al. (1987) found the cross-sectional area of the elbow flexors of bodybuilders to be 60% greater than that of untrained males, while Schantz et al. (1983) found the knee extensors of another group of bodybuilders to be approximately 40% greater in area than those of age matched physical education students. Longitudinal training studies are superior to cross-sectional studies because the effects of training upon muscle size can be demonstrated over time in the same individual(s). Such studies have shown increases in muscle cross-sectional area of 23% (elbow flexors, ultrasound measures) after 100 days of training (Ikai & Fukanaga, 1970), 16% and 23% (elbow flexors, males and females respectively, CAT scans) after 16 weeks of training and 6% (quadriceps) after 15 training sessions (Young et al. 1983). Recently Narici et al. (1989) and Sale et al. (1990), have reported increases of up to 8.5% and 21% respectively in the cross-sectional area of knee extensor muscles as measured by computed tomographic scans after 60 days and 22 weeks of training.

Increases in muscle cross-sectional area may theoretically result from increases in the size of individual muscle fibres, from increases in muscle fibre number or from the proliferation of connective tissue.

1.1.3. THE EFFECTS OF STRENGTH TRAINING ON MUSCLE MORPHOLOGY

The stimulus of progressive resistance exercise to induce muscle hypertrophy is potent and has been demonstrated in animals undergoing a net weight loss, in the absence of endocrine signals for hypertrophy and even in the presence of endocrine signals for muscle depletion. (Goldberg et al., 1975; MacDougall, 1986)

All muscle fibre types have been shown to increase in cross-sectional area in response to training, with greater hypertrophy occurring in the Type II fibres (Thorstensson, 1976; MacDougall et al., 1980.). The magnitude of this increase may be up to 39% and 31% in Type II and Type I fibres respectively, following 5-6 months of heavy weightlifting training (MacDougall et al., 1980).

A muscle fibre's cross-sectional area is increased after strength training by the addition of actin and myosin filaments to the myofibrils, though filament packing density does not change (MacDougall, 1986). Increases in fibre size are also accompanied by increases in connective tissue. The absolute amount of connective tissue in the muscle increases, but the relative amount decreases (Sale et al., 1987).

It has been argued that increases in muscle cross-sectional area may be the result of not only increases in muscle fibre size but also in fibre number. Such hyperplasia has been demonstrated in some animal studies, (Gonyea et al., 1977; Gonyea, 1980), but others (Gollnick et al., 1981; Gollnick et al., 1983), have failed to confirm these observations and have criticized the previous authors work for having methodological errors. Exact counts of fibre numbers in humans engaged in training studies are not possible as such research necessitates the surgical removal of the muscle. However, estimates of muscle fibre numbers may be determined from CAT measures of muscle cross-sectional areas, which are corrected for connective tissue content and then divided by mean fibre areas determined from needle biopsy samples. Such studies have shown that elite and intermediate male bodybuilders have similar numbers of fibres in the biceps brachii as untrained males, indicating that in humans hyperplasia probably does not occur (MacDougall et al., 1982). This same research group reported that elite bodybuilders possessed more muscle fibres in the triceps brachi than a group of trained controls, but since they found individuals who were equally as well trained as the bodybuilders but with fewer than normal fibre numbers, they concluded that the bodybuilders may have been genetically endowed with more fibres at birth rather than developing them through training (MacDougall et al., 1982).

1.1.4. NEURAL ADAPTATIONS TO RESISTANCE TRAINING

As well as increasing contractile mass, it is possible to increase strength through the recruitment of synergistic muscles and by enhanced control of motor units (Gonyea and Sale 1982; Sale, 1988; Enoka, 1988;

Jones et al., 1989). During the early stages of training the majority of adaptations are thought to be neural. Up to 80% of strength gains after two weeks of training can be attributed to neural factors (Moritani & de Vries, 1979). Similarily, voluntary strength can be increased in the absence of muscle hypertrophy in short term training studies of less than 8 weeks (Thorstensson, 1976; Moritani & de Vries, 1979). Moreover, when increases in whole muscle, or muscle fibre size do occur, they are much less than the increases in voluntary strength. For example, Ikai and Fukanaga (1970) found a 92% increase in voluntary strength after 100 days of training, but only a 23% increase in the cross-sectional area of the elbow flexors.

Up to the 5th week of training increases in maximal voluntary contractions of 20% (McDonaugh et al., 1983) and 30% (Davies and Young, 1983), have been reported without a corresponding increase in evoked twitch or tetanic tensions. If hypertrophy were responsible for the increases in voluntary strength one would expect to see similar increases in evoked contraction strength, as the subjects would have more contractile machinery rather than just an enhanced ability to utilize what they already have to greater advantage.

Strength training also results in an increased integrated electromyogram (IEMG), indicating an increase in the number of active motor units and/or an increase in their firing frequency (Hakkinen & Komi, 1983) with most of this change occurring in the first 3-4 weeks of training (Moritani & de Vries, 1979).

Finally, strength training of one limb has been shown to increase the strength of an untrained contralateral limb. Ikai and Fukanaga (1970) found a 30% increase in the strength of an untrained contralateral limb with no increase in the cross-sectional area and suggested that the strength gain was brought about through enhanced motor unit control.

1.2. AGE RELATED CHANGES IN SKELETAL MUSCLE

1.2.1. DECREASED MUSCULAR PERFORMANCE

Age related changes in various parameters of human skeletal muscle have been well documented. For example, aging is associated with general decreases in strength (Vandervoort et al., 1986; Gerdle & Fugl-Meyer, 1985; Murray et al., 1980; Young, 1985; Essen-Gustavssen & Borges, 1986). Isometric and dynamic strength have been found to increase in individuals up to the age of 30, change very little up to the age of 50 and then to slowly decline thereafter (Montoye & Lamphiear, 1977;

Larsson et al., 1979). The decrease in strength has been noted in both the upper (Moritani & de Vries, 1980) and lower limbs (Murray et al., 1985). On the basis of electrophysiological techniques, Campbell et al. (1973) suggested that one factor contributing to the weakening of aging muscle is a reduction in the number of functioning motor units, particularly the type II moiety; the fibre type grouping and enclosed fibres that are seen in histological sections of older muscles lend support to this finding (Grimby et al., 1982). Although changes in connective tissue and fat content of older muscle have been noted (Tzankoff et al., 1977; Borkan et al., 1983), aged muscle has been found to have similar enzymatic and capillary supplies as young muscle (Orlander et al., 1978). In addition it has been demonstrated that while older individuals may exhibit a weaker and prolonged evoked twitch contraction response, they show no evidence of decreased motor unit activation (Vandervoort & McComas, 1986) and so it has been suggested that decreases in muscle performance that occur with advancing age are the result of quantitative rather than qualitative differences within the muscle (Grimby & Saltin, 1983). It has also been suggested that inactivity may be a major contributor to muscle wasting and weakness (Campbell et al., 1973; Lexell, 1986).

1.2.2. DECREASES IN WHOLE MUSCLE AND MUSCLE FIBRE SIZE

Advancing age appears to be associated with decreases in lean tissue mass and a redistribution of subcutaneous and intra-abdominal fat stores (Borkan et al. 1983). Studies using computerized x-ray tomography (Immamura et al., 1983) have indicated that much of the reduction in lean tissue is because muscle size decreases with age; as much as 25% in the maximum cross-sectional area of the quadriceps between the third and eighth decade of life (Young et al., 1985).

Decreases in muscle mass and cross-sectional area can result from decreases in muscle fibre number (Lexell et al., 1986), muscle fibre size (Essen-Gustavssen & Borges, 1986) or a combination of the two. The majority of the evidence suggests that it is the Type II fibres which seem most affected, fibre cross-sectional areas decreasing by 5-10% in subjects over sixty years of age (Grimby & Saltin, 1983) and their relative distribution diminishing from 60% at age 30, to only 45% at age 70, (Larsson et al., 1978, 1979, 1983). Evidence from electrophysiological studies indicates that the loss of Type II fibres is secondary to motoneuron cell death (Campbell et al., 1973).

It has been demonstrated (Davies & White, 1983; Vandervoort & McComas,1986) that, when compared to young muscle, elderly muscle is slower contracting and weaker, producing significantly lower maximal twitch torques, increased times to peak twitch tension and slower half relaxation times. Sica and McComas (1971), however, found no such relationship between age and contraction time, but on the basis of relaxation-time data have speculated that the series elastic element of elderly muscle may be decreased. In contrast to the decreases in muscle size and contractile properties in aging muscle, there appears to be little deterioration in metabolic capacity (Essen-Gustavssen & Borges, 1986). Taking this into consideration, and based on the similar reductions in muscle mass and strength with aging, and evidence for the preservation of specific tension, Grimby and Saltin (1983) have suggested that it is quantitative rather than qualitative changes within muscles which account for most of the age related strength loss.

1.2.3. PREVIOUS TRAINING STUDIES IN THE ELDERLY

It has been suggested that declining physical activity may contribute to age related strength loss (Aniansson et al., 1983). If this is so, progressive resistance strength training may serve to decrease or reverse the rate of strength decline in the elderly. To date, few strength training studies in the elderly have been published, and the majority of these have not used progressive resistance models, but rather have involved the use of isometric training (Kaufman, 1985), calisthenics and elastic bands, (Aniansson & Gustavsson, 1981; Aniansson et al., 1984), or have dealt with very small muscle groups such as the index finger (Chapman et al., 1972) or the abductor digiti minimi (Kaufman, 1985).

Though subjects have increased strength in all of the above studies, the degree of increase has varied. Those studies employing calisthenics or elastic bands as the training stimulus have shown strength increases of only 9-22% (Aniansson & Gustaffsson, 1981) and 7-11% (Aniansson et al., 1984). Isometric training increased plantarflexion and knee and hip extension strength from 29-57% (Perkins & Kaiser, 1961), and little finger adduction strength by 72% (Kaufman, 1985). This latter figure probably reflects more upon the peculiar nature of the movement involved rather than the efficacy of the training protocol. Dynamic training studies have produced increases in plantarflexion and knee and hip extension strength from 41-64% (Perkins & Kaiser, 1961), index finger flexion strength of 33% (Chapman et al., 1972) and elbow flexor strength of 23% (Moritani & de

Vries, 1980). Recently, Frontera et al. (1988) have published increases of 107 and 227% in the strength of elderly subjects' knee extensors and flexors respectively after 12 weeks of dynamic resistance training. Again, such striking increases may perhaps be attributed to the nature of the exercise involved in the training and measurement of knee extension and flexion strength.

In those studies which have used untrained contralateral limbs as controls, cross-training effects have been observed and these increases in strength of an untrained limb occurring in the absence of hypertrophy, as well as the relatively rapid increases in strength, have led researchers to conclude that much of their subjects' improvements have been due to neural factors (Perkins & Kaiser, 1961; Chapman et al., 1972; Kaufman, 1985). However, it may be that such conclusions have been drawn as a result of training protocols insufficiently intense or long enough to produce hypertrophy, or the use of testing methods incapable of accurately detecting it. Moritani and de Vries (1980) felt that their elderly subjects increased strength after training because of neural adaptations, indicated by increases in maximal IEMG in the absence of hypertrophy. However, their study was of only 8 weeks duration, subjects trained with a load corresponding to only 66% of their 1 RM and muscle cross-sectional area was determined from limb girth measurements corrected for skinfold thickness.

Recently CT scans have been used to determine muscle cross-sectional areas in combination with a strenuous progressive resistance training protocol (Frontera et al., 1988). In this group, after 12 weeks of training, subjects were found to have an 11.4% increase in total muscle area of the thighs, including a 9.3% increase in the area of the quadriceps. These findings were supported by increased muscle fibre areas of 33.5% and a 27.6% in the Type I and II fibres respectively, and by increased myofibrillar protein turnover, suggesting that hypertrophy can occur in an older population in response to training. While other studies have found similar increases in fibre areas in response to training in the elderly, (Larsson et al., 1982), it should be noted that there are reports of *strength gains accompanied by only 5-9% (NS)* increases in fibre area (Aniansson & Gustafsson, 1981).

SUMMARY AMD STATEMENT OF PURPOSE

The practical implications of any study into the effects of strength training in an older population are to improve the quality of life of the elderly. The well documented substantial deterioration of muscle mass and fibre number with advancing years, with the associated decrease in muscular strength, results in a reduced functional capacity, often resulting in dependency and institutionalization. If it is possible to increase the strength of elderly individuals through resistance training, this may translate into an improved ability to perform many of the activities of daily living, thereby making older individuals better able to look after themselves and decreasing the need for geriatric support facilities.

Studies in this area utilizing calisthenics and rubber bands as resistance have yielded encouraging but inconclusive results. Few studies have utilized progressive resistance weight training programs for their subjects, but such models seem ideal for improving the performance of subjects in activities of daily living because they yield large increases in dynamic strength which may conceivably carry over to many daily tasks. The benefits of isometric training programs are considerably more restricted and limited to the joint angles trained at. Many studies which have employed progressive weight training models have examined obscure muscle groups such as the finger flexors and abductors and findings from them cannot be extrapolated to the larger muscles of the body.

The purpose of this study was to investigate the adaptations to strength training in a group of 60-70 year old men, utilizing a unilateral arm training model in which one arm served as a within subject control. Electrophysiological techniques, including the interpolated twitch method were employed in combination with measures of muscle and muscle fibre cross-sectional areas determined from CT scans and needle biopsy samples. In this way it could be determined if increases in muscle cross sectional areas would translate into increases in twitch torques, rates of torque development and half relaxation time, providing evidence of increases in intrinsic strength independent of volition. To date no other such study has been undertaken.

CHAPTER 2

METHODS

2.1.1. SUBJECTS

Fourteen male volunteers aged 60 - 70 (mean 62.8), took part in the study. All subjects participated with their own informed consent in accordance with the policies of the McMaster University President's Committee on Ethics of Research On Human Subjects. Prior to acceptance into the study, subjects performed a progressive incremental cycle ergometer test to detect any signs of latent heart disease or pulmonary impairment; such individuals were excluded from the study.

2.2.1. TRAINING AND STUDY DESIGN

Strength training was done 3 alternate days per week for 12 weeks. Bilateral leg press, supine bench press and seated dead lift exercises were done on a multistation weight training machine (Global Gym Inc., Downsview Ont., Canada); bent leg abdominal curls were done on a padded station on the floor. Dead-lift and abdominal curl exercises were included in the study to provide the subjects with a well rounded training program; however, no measures of performance were made on these exercises. Subjects trained the elbow flexors of one arm only, on a custom-built weight lifting apparatus (Rubicon Industries, Stony Creek, Ontario); the arm to be trained was selected randomly, the non-trained arm serving as a within subject control. Exercises were done in a circuit set system with no more than 2 min rest between sets. Subjects performed 10 repetitions per set of bench press and arm curl exercises, 15 repetitions per set of leg presses and 12-20 repetitions of dead-lift and abdominal curls. Although only one arm performed the arm curl exercise, the elbow flexors of both arms probably received a moderate stimulus from the bench press and dead-lift exercises. Subjects progressed from performing 2 sets of each exercise at 50% of their initial 1 RM, (1 repetition maximum, the heaviest weight lifted for one repetition), to 4 sets at 70-90% of their initial 1RM, over the course of the study (Table 1).

2.3. MEASUREMENT OF VOLUNTARY STRENGTH

2.3.1. WEIGHT LIFTING STRENGTH

Weight lifting strength was measured as the highest 1 RM achieved on the training apparatus over two separate days of testing. After a suitable warm-up subjects performed single repetitions with progressively heavier weights, resting 2-3 min between attempts. The heaviest weight that subjects could lift once in this manner was determined to be their 1 RM for that exercise. The movements tested included: 1) elbow flexion of each arm separately on a custom-made weight lifting device; 2) bilateral leg press (hip and knee extension, ankle plantarflexion); 3) bench press. The latter two movements were tested on a multistation weight-training apparatus. In addition, after training, endurance was measured as the number of repetitions done in each exercise with the pre-training 1 RM.

2.3.2. ISOKINETIC CONTRACTION STRENGTH

Isokinetic, concentric contraction strength during leg press and elbow flexion movements was measured as peak torque on a Cybex dynamometer (Lumex, Inc., Ronkonkoma, New York). Elbow flexion of each arm was tested separately. A series of 3 maximal voluntary contractions (MVCs) was performed in a random order at

TABLE 1

The circuit training scheme employed in this study. The progression in the left panel was employed for the bench press (10 reps), double leg press (15 reps) and single arm curl (10 reps) exercises. The progression in the right panel was followed for abdominal curl exercise and seated dead lift at a constant weight of 25 kg.

WEEK	Sets and % of initial 1RM				Sets and # of reps			
1	50	50			12	12		
2	50	70	70		12	12	12	
3	50	70	70		12	12	12	
4	60	70	80		12	12	12	12
5	60	70	70	80	12	12	12	12
6	60	70	70	80	12	12	12	12
7	60	70	70	80	12	12	12	12
8	60	70	70	85	15	15	15	15
9	60	70	75	85	15	15	15	15
10	70	70	75	85	20	20	20	20
11	70	70	80	90	20	20	20	20
12	70	80	90	90	20	20	20	20

Note: From the sixth week of training on, subjects trained at 10 - 12 repetitions to failure after an initial warm up set. The percentages of initial 1RM listed here are therefore approximations based upon the weights the subjects were able to train with.

angular velocities of 30, 120, 180, 240 and 300°/s. Since the elbow joint was aligned with the axis of rotation of the Cybex, the arm velocity measured at the elbow corresponded to the lever arm velocity of the machine. The best of the three trials at each velocity was taken as the pre-training value. Isokinetic bilateral leg press strength was measured on a leg press apparatus coupled to the Cybex dynamometer (Vandervoort et al., 1984). This apparatus, by means of a 4:1 gear reduction mechanism, enables the Cybex to accommodate the potentially large torques which can be generated during a leg press manoeuvre. Such a mechanism not only reduces the torque registered by the Cybex to one fourth of that produced by the subject, (the subject's torque is then multiplied by 4 to obtain his actual value), but also reduces the set lever arm velocity of the Cybex by a similar magnitude. As a result, if the velocity selected on the Cybex dial was 60 °/s, the true velocity of the Cybex lever arm would be 15 °/s. While subjects were actually tested throughout the velocity range of the instrument, the highest velocity was limited to 75 °/s. Thus, three trials were done at lever arm velocities of 15 and 75 °/s. The peak torque of the best of the three trials was taken as the pre-training value.

Maximal voluntary isometric strength was measured on a custom-built apparatus (described in detail in section 2.4.2.). Maximal voluntary elbow flexion strength of each arm was tested separately by having subjects perform 2 MVCs interspersed with 2 min of rest at randomly selected joint angles of 75, 120 and 165 °; the higher of the 2 peak torques being taken as the pre-training value. The extent of motor unit activation during the maximal voluntary contractions (MVCs) was assessed using the interpolated twitch technique (Belanger & McComas, 1981), described in detail in section 2.4.3.

2.4. MEASUREMENT OF EVOKED CONTRACTILE PROPERTIES

2.4.1. APPARATUS

A custom-built device comprised of two aluminum plates hinged together was used to secure subjects' elbows at angles of 75, 120 and 165° for the measurement of voluntary and evoked torque. One plate, on which the subject's upper arm rested, remained secured in the horizontal position to a wooden bench. The second plate, to which the subject's forearm was attached in the supinated position by means of velcro straps, could move freely. The subject's elbow was aligned with the device's axis of rotation and could be fixed at the desired joint angle determined from a scale located on the side of the apparatus. A clamp secured the device at the desired angle and torque was measured with a strain gauge located on the shaft linking the two plates together. The signal from the strain gauge was relayed through an amplifier to a storage oscilloscope (HP 120 1B) and a computer (PDP 1103 Digital Equip. Corp.) where it was analyzed on line.

2.4.2. **TESTING PROCEDURE**

Subjects were seated in a chair with the bench and the arm apparatus located in front of them. The upper arm was positioned horizontally on the stationary plate and the forearm was secured to the second plate. Since MVC's can potentiate twitch responses, (Vandervoort et al., 1983), twitch contractions were evoked prior to voluntary contractions. Lead plate electrodes, wrapped in gauze soaked with conductive cream, were attached to the palmar surface of the forearm and the belly of the biceps. Twitches were elicited using rectangular voltage pulses of 50 μs duration from a Devices, (Medical Systems Corp.) stimulator. Torque was read from the storage oscilloscope, and when no further increase in torque was noted with increases in stimulating voltage it was assumed that the muscle was maximally stimulated. After the twitches, subjects were given two attempts at each angle to perform an MVC of the elbow flexors, the highest of the scores being used for analysis. Twitch and maximal voluntary torque were measured at angles of 75, 120, and 165° in a randomized order. Computer analysis of the twitches yielded the following measures: peak torque (N.m), time to peak torque (ms), half-relaxation time (ms), maximum rate of torque development (N.m/s), maximum rate of torque relaxation (N.m/s), and torque-time integral (N.m.s).

2.4.3. **INTERPOLATED TWITCH TESTING**

During MVC testing, interpolated twitch contractions were used to determine the extent of motor unit activation (Belanger & McComas,1981). While subjects performed maximal voluntary contractions, peak torque production was determined from a storage oscilloscope. When subjects were determined to be generating peak torque with their elbow flexors a supramaximal stimulus was delivered to the elbow flexor muscles using the technique described above. Any motor units that had not been recruited during the MVC or were not firing at their optimal frequencies, should produce a detectable twitch response after being stimulated in this manner.

2.5.1. MEASUREMENT OF MUSCLE CROSS-SECTIONAL AREA

The cross-sectional area (cm^2) of the flexors and extensors of the elbows and knees as well as the area of the humerus and femur was determined using computerized tomographic scans (Model 20-30, Ohio Nuclear) pre- and post-training. The two legs were scanned simultaneously through a point corresponding to 50% of the upper leg length as measured from the head of the fibula to the greater trochanter of the femur while the subjects lay in a supine position. The arms were scanned individually while abducted 90°, with the elbow fully extended, through a point corresponding to 40% of the upper arm length as measured from the lateral epicondyle of the humerus to the acromion process of the scapula. Slide photographs taken of the scan images were projected on to blank paper and tracings made of the flexor, extensor and bone compartments to be studied. Compartment areas were measured using a computerized digitizing platform (Compucolour Inc.).

2.6.1. MEASUREMENT OF MUSCLE FIBRE CHARACTERISTICS

Muscle fibre characteristics of the biceps brachii in trained and untrained arms were determined from needle biopsy samples. After being oriented under a dissecting microscope, muscle tissue samples were secured in Tissue Tek OCT embedding medium, frozen in isopentane which had been pre-cooled in liquid nitrogen, and then stored in a freezer at -50° C. Sections 10 μm thick were taken from the samples and mounted on slides. Fibre type was determined using the method of Padykula and Herman (1955) at a pre-incubation pH of 10.0.

From a single stained section of muscle tissue, photomicrographic slides with non-overlapping fields were taken on an Olympus BHA microscope at a magnification of 10X with an Olympus photo-micrographic camera (model PM-10A). These slides were then projected onto a computerized digitizing platform (Compucolour Inc.) for fibre area analysis. Measurements included cross-sectional areas of both Type I and II fibres and fibre type distribution. An average of 100 type I and II fibres per subject pre-training and 78 type I and 88 type II fibres per subject post-training were used for fibre area analysis. For muscle fibre distribution measures, all fibres visible on the slides, whether partial or whole were counted.

2.7.1. STATISTICS

Descriptive statistics included mean and standard error. Training effects were evaluated using between and within split plot ANOVA's with one between subject factor. Factors for these analyses included; arm, angle, velocity and time with repeated measures on the time factor. 1 RM results for bench press and leg press were analyzed using one way ANOVA's. Post hoc mean comparisons were examined using the Tukey "A" test. Statistical significance was accepted at $p \leq .05$.

CHAPTER 3

RESULTS

All subjects were able to successfully complete the study and no injuries were sustained as a result of training.

3.1. VOLUNTARY STRENGTH

3.1.1. WEIGHTLIFTING CAPACITY

The 1 RM values for all three weightlifting exercises increased significantly ($p<0.001$) following training (Fig. 1 & 2). The improvement in the single arm curl 1RM in the trained arm (48.4%, 11.2 to 16.7 kg) was greater than in the control arm (12.7%, 11.9 to 13.4 kg; $p< 0.05$). In addition, after the training period subjects were able to perform an average of from 7-19 repetitions (Table 2, Appendix B) with a weight corresponding to their pre-training 1 RM.

3.1.2. ISOKINETIC STRENGTH

Maximum isokinetic strength in the bilateral leg press manoeuvre improved by 18% (201 to 237 N.m) at .26 rad/s (15°/s) and 17% (135 to 158 N.m) at 1.31 rad/s (75°/s) following training ($p<0.001$) (Fig.3). During isokinetic elbow flexion exercise at the 5 angular

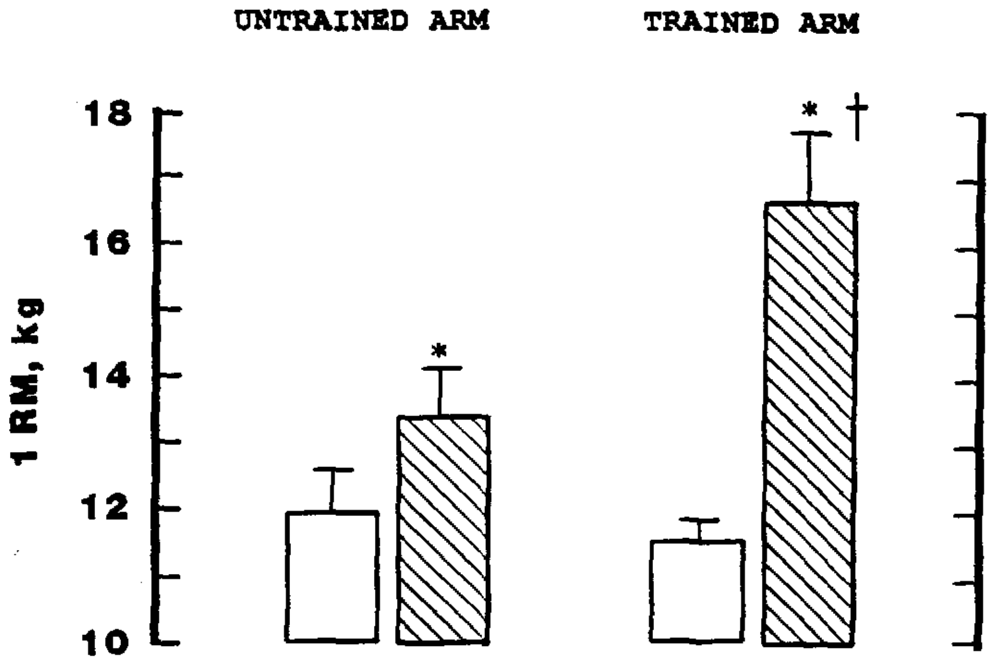

FIG. 1. Maximal weight-lifting capacity (1-repetition maximum, IRM) in trained and untrained arms before (open bars) and after (hatched bars) training. *$P<0.05$, change after training and †$P<0.05$, difference between arms.

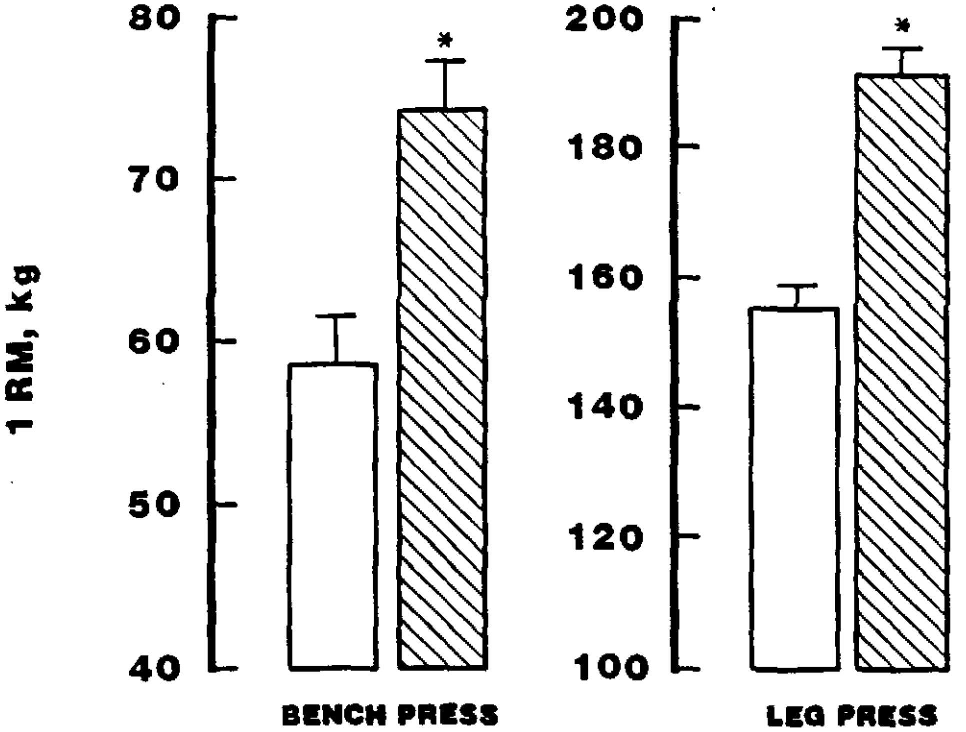

FIG. 2. Maximal (means ± SE) weight lifting capacity (1RM) in bench press and bilateral leg press exercises, measured before (open bars) and after (hatched bars) 12 wk of training. *$P<0.001$, increase with training.

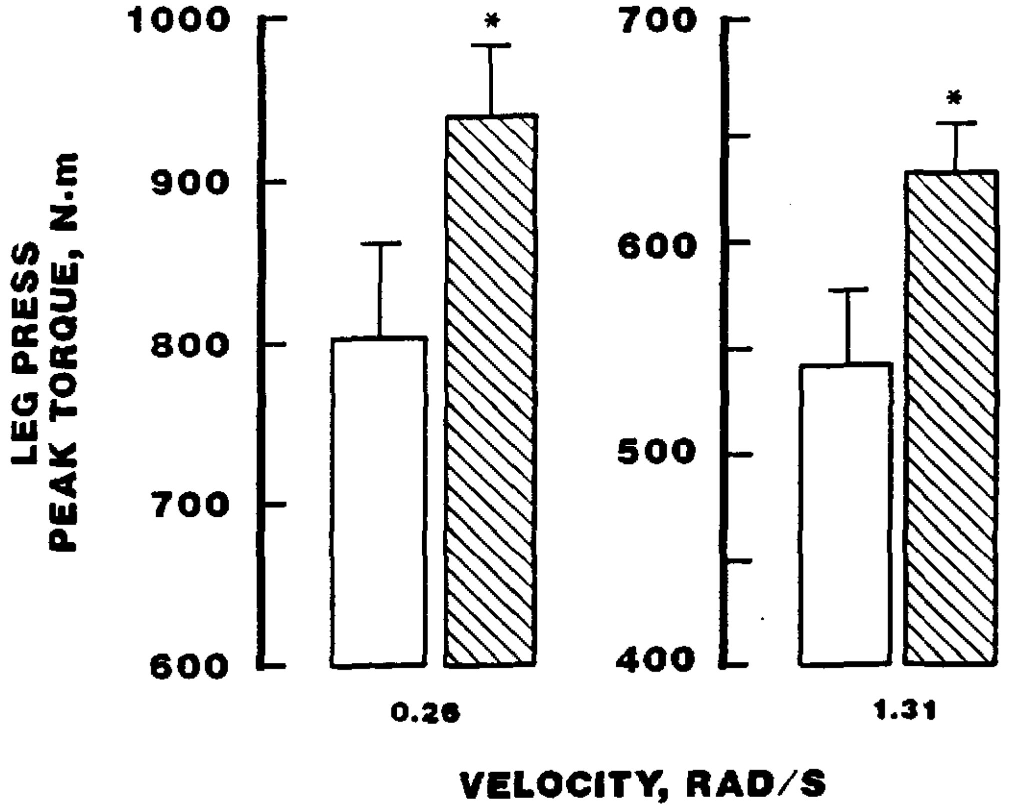

FIG. 3. Maximal (means ± SE) isokinetic leg press torque at 2 angular velocities before and after training. *$P<0.0001$, increase with training.

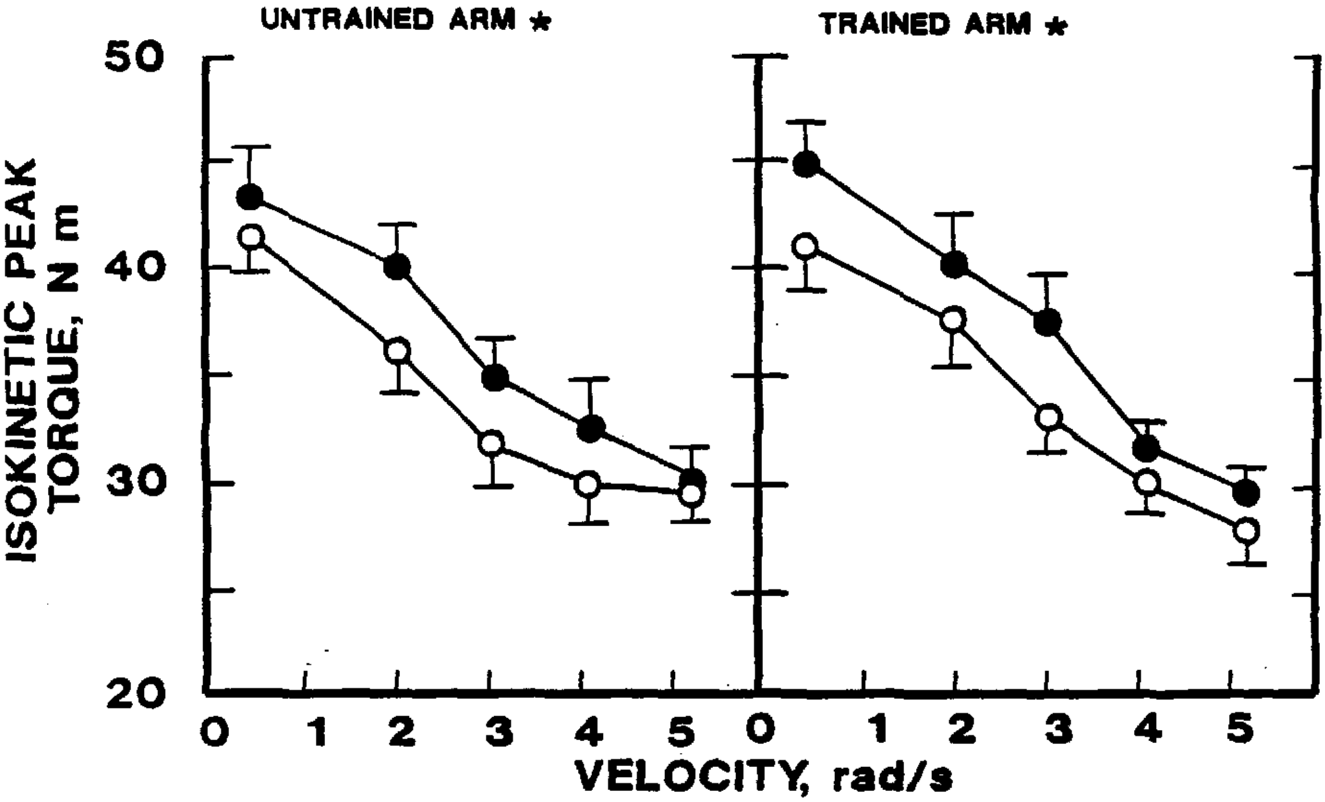

FIG. 4. Maximal isokinetic torque during elbow flexion exercise in both arms before (open circles) and after (filled circles) training. *$P<0.01$, overall increase after training.

velocities, the mean increases in the trained arm (8.8%; $p<0.01$) were similar to those in the control arm (6.5%) (Fig. 4).

3.1.3. ISOMETRIC STRENGTH

Peak elbow flexion torque varied with joint angle, but there was no significant increase in torque in either arm after training (Fig.5). The absence of additional isometric tension in response to an interpolated stimulus confirmed that the subjects were able to achieve almost complete motor unit activation prior to (97.5%) and following (98%) the weight training.

3.2.1. EVOKED MUSCLE CONTRACTILE PROPERTIES

Training increased the maximum evoked twitch torque at joint angles of 2.04 rad(120°) (9.1%, 7.5 to 8.2 N.m) and 2.81 rad(165°) (11.6%, 7.5 to 8.4 N.m) in the trained arm, and at an angle of 2.81 rad (165°) (11.9%, 7.3 to 8.2 N.m) in the untrained arm ($p<0.05$) (Fig. 6). There was also a significant decrease ($p<0.05$) in the twitch torque of the untrained arm at 2.04 rad (120°) (11.2%, 7.7 to 6.8 N.m). The twitch torque-time integral increased significantly ($p=0.007$) in the trained arm at elbow joint angles of 2.04 and 2.81 rad (120 and 165°), but there was no change in the control arm (Fig.

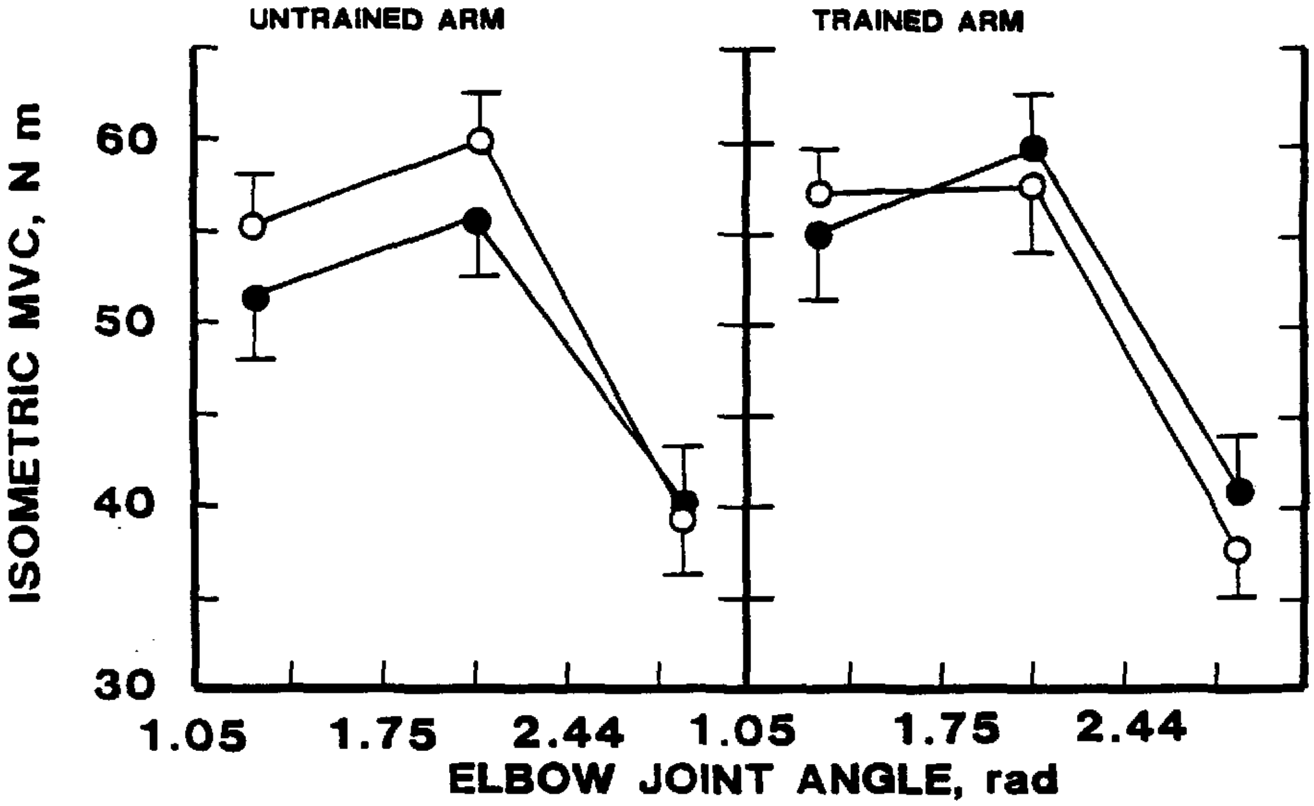

FIG. 5. Maximal isometric torque (maximum voluntary contraction, MVC) during elbow flexion exercise in both arms before (open circles) and after (filled circles training.

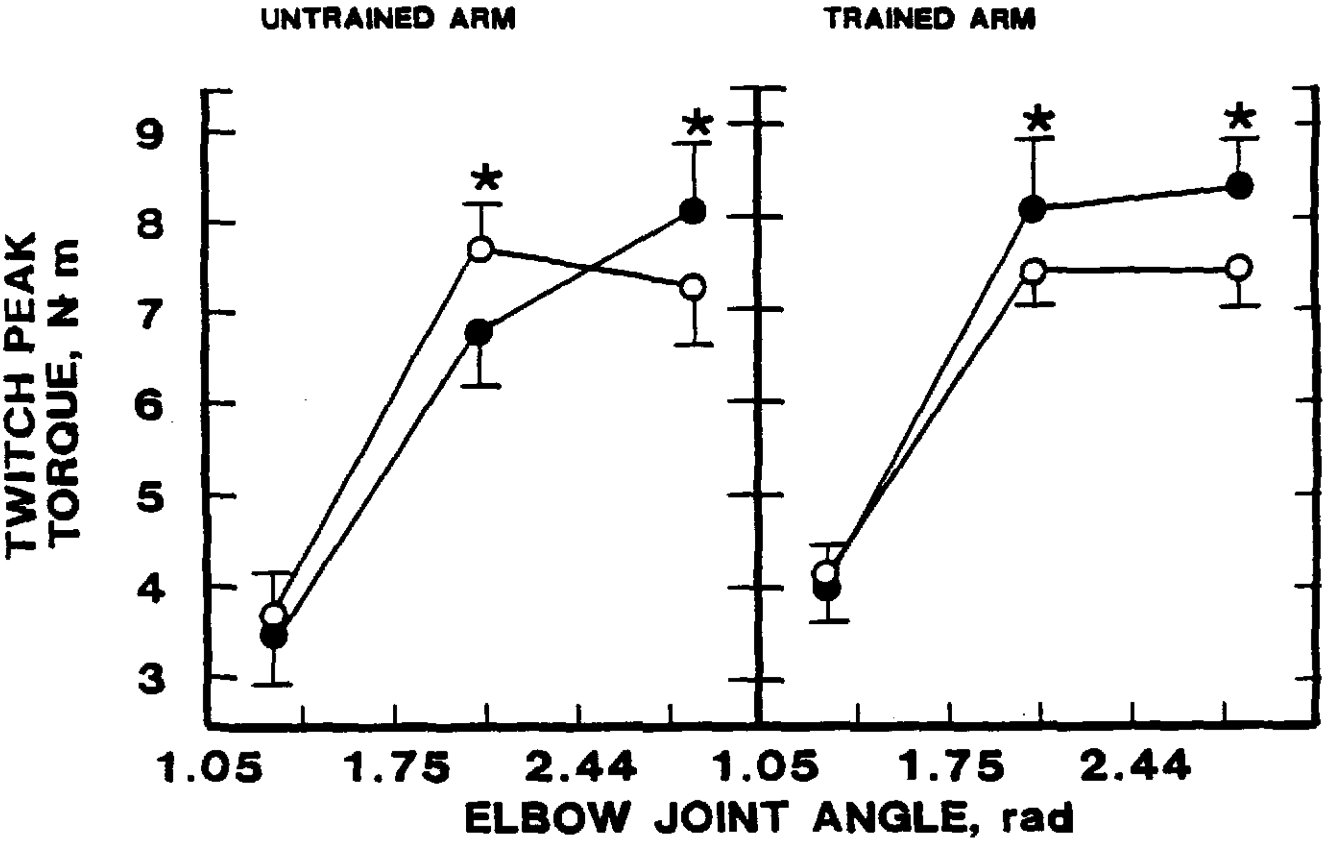

FIG. 6. Maximal twitch torque during electrically evoked contractions of elbow flexors of both arms before (open circles) and after (filled circles) training. *$P<0.05$, change after training.

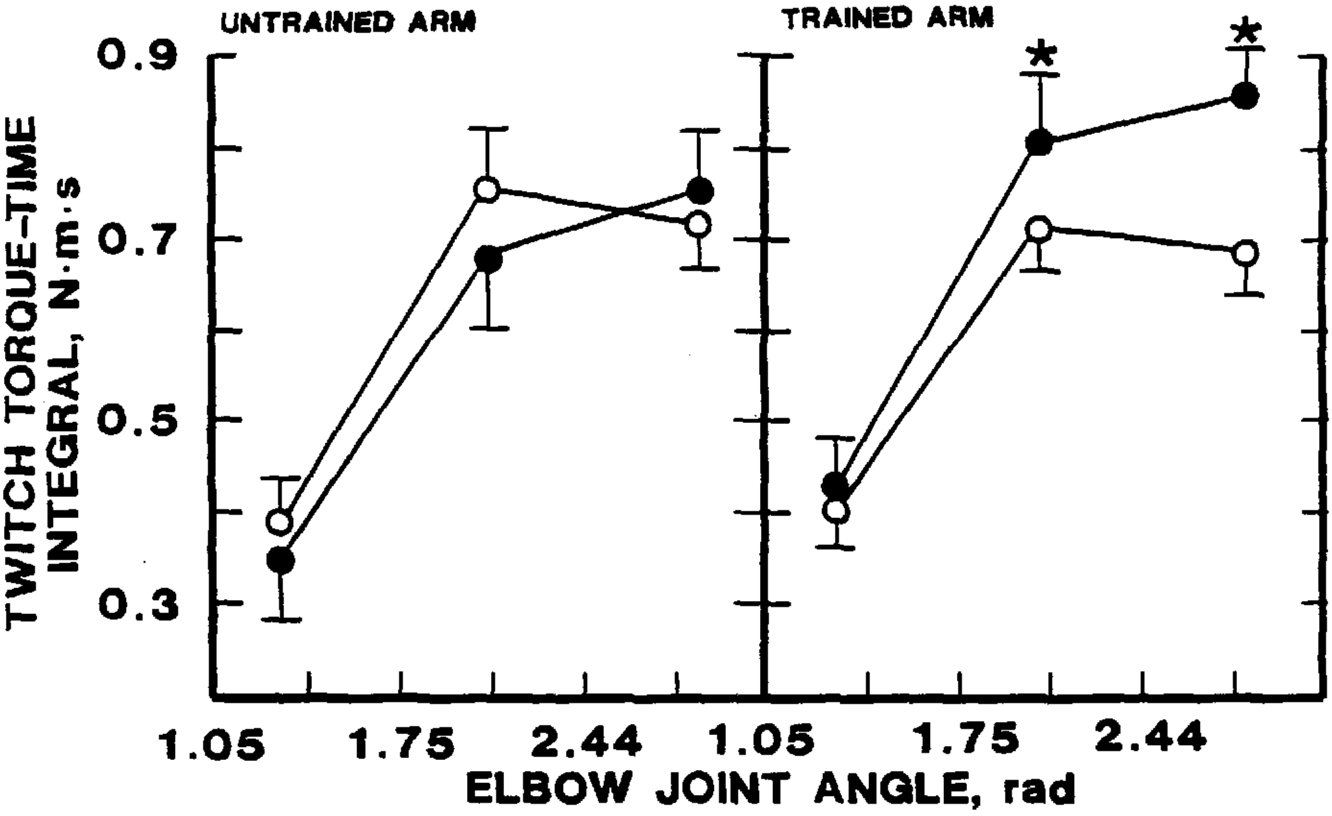

FIG. 7. Maximal torque-time integral during electrically evoked contractions of elbow flexors of both arms before (open circles) and after (filled circles) training. *P=0.007, change after training.

7). The maximum rate of torque development decreased significantly ($p<0.05$) in the untrained arm at 2.04 rad (120°) (229.6 to 204.8 N.m/s) and increased significantly in both arms at an angle of 2.81 rad (165°) (211.9 to 237.8 and 202.7 to 232.5 N.m/s, trained and untrained arms respectively; $p<0.05$), but not at the other joint positions (Fig. 8). The half-relaxation times were prolonged in the trained arm at all joint angles following training ($p<0.05$), but were unchanged in the control arm (Fig. 9). No differences were seen in time to peak twitch torque or maximum rate of torque relaxation in either arm before or after training (Figs 10 & 11).

3.3.1 MUSCLE CROSS-SECTIONAL AREA

During the course of the study there was a significant ($p<0.001$) increase in cross-sectional area (CSA) of the elbow flexors of the trained arm (16.7 to 19.6 cm^2, 17.4%) (Fig. 12), but no change in the control arm. In contrast, in the control arm there was a small but significant ($p=.035$) increase in the mean maximum cross-sectional area of the elbow extensors (triceps brachii) (22.1 to 23.7 cm^2), but no significant change in the trained limb. It should be noted that the terms "trained" and "untrained" refer only to the elbow flexors

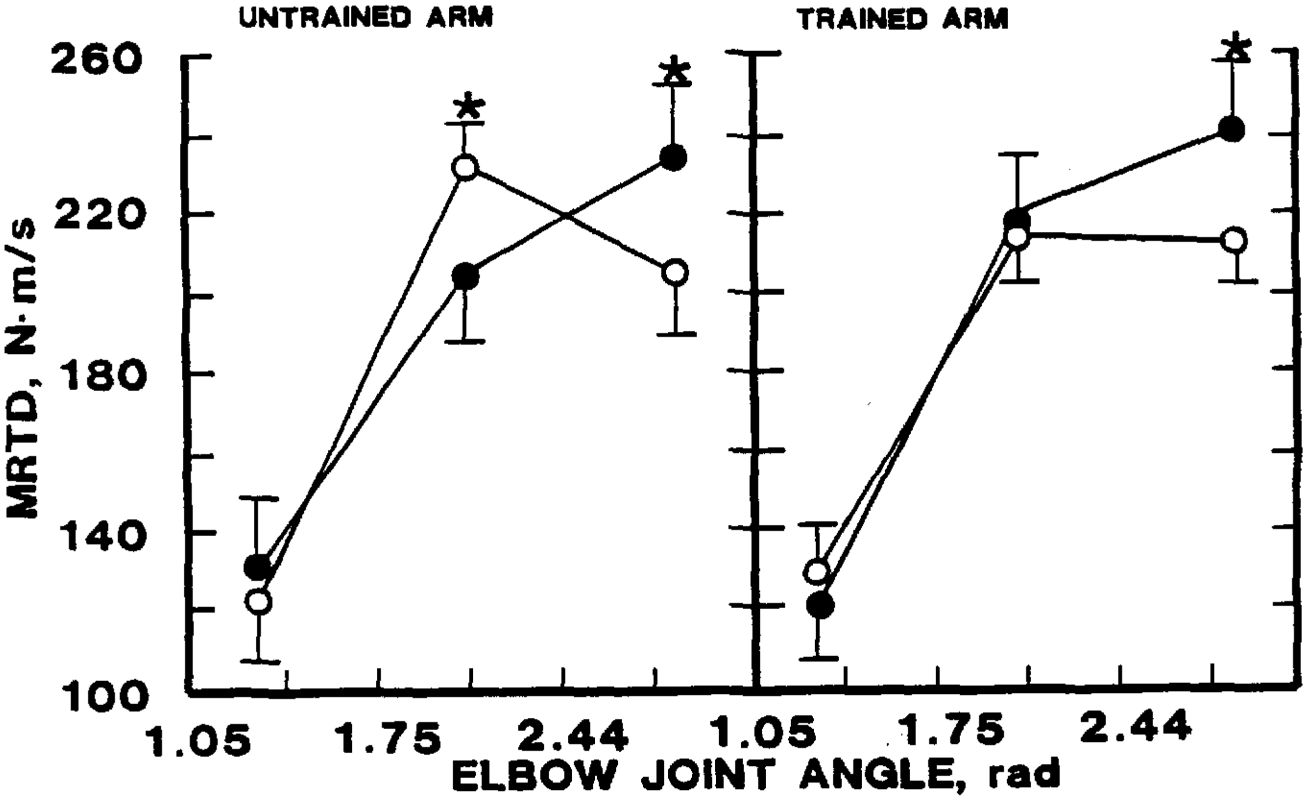

FIG. 8. Maximal rates of torque development (MRTD) during electrically evoked twitch contractions of elbow flexors of both arms before (open circles) and after (filled circles) training. *$P<0.05$, change after training.

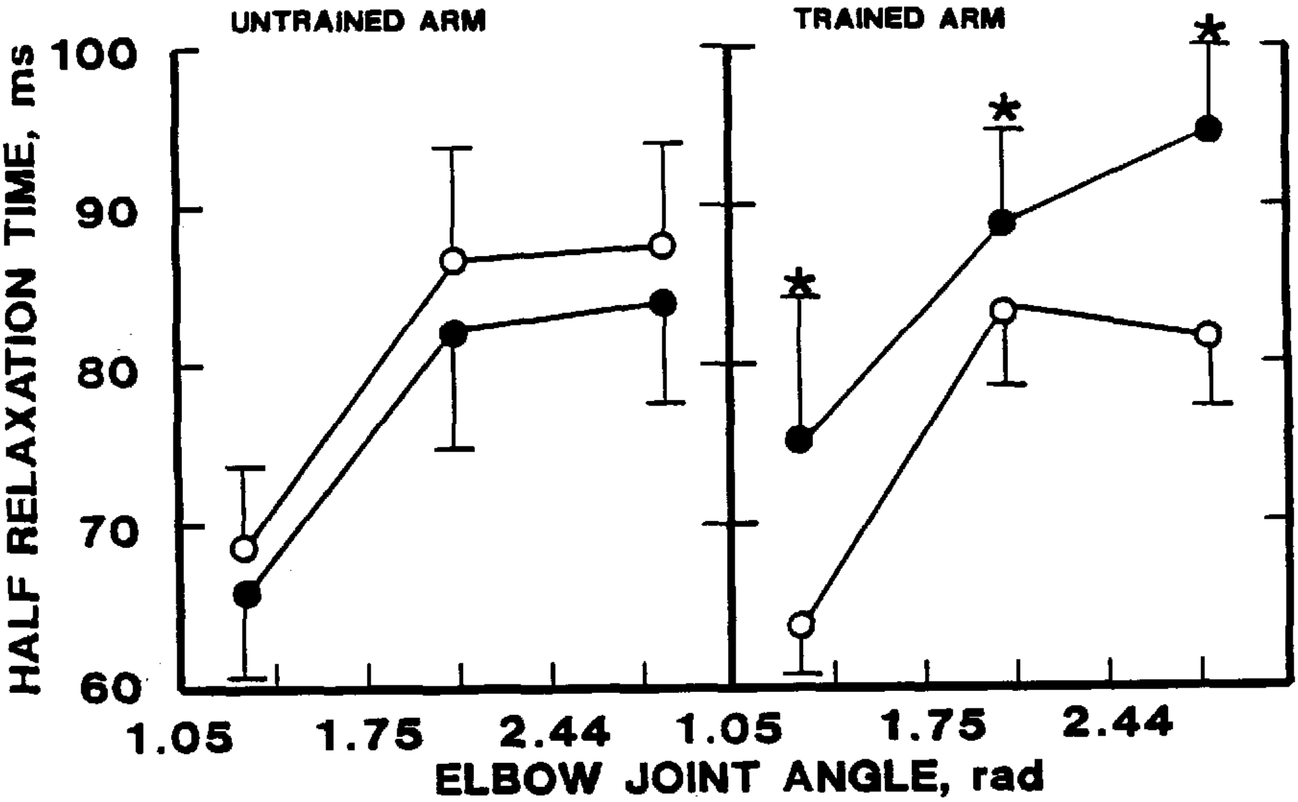

FIG. 9. Half-relaxation times during electrically evoked twitch contractions of elbow flexors of both arms before (open circles) and after (filled circles) training. *$P<0.05$, change after training.

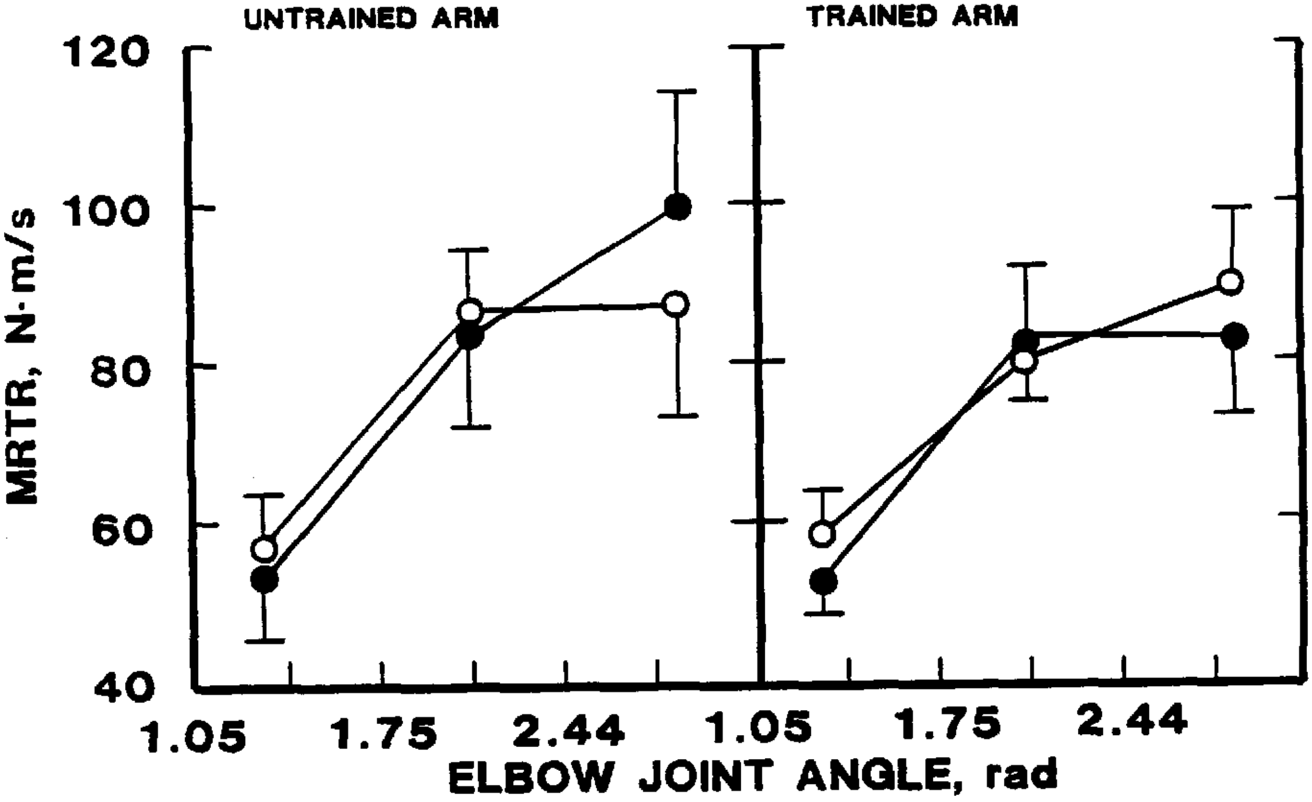

FIG. 10. Maximal rates of torque relaxation (MRTR) during electrically evoked twitch contractions of elbow flexors of both arms before (open circles) and after (filled circles) training. *$P<0.05$, change after training.

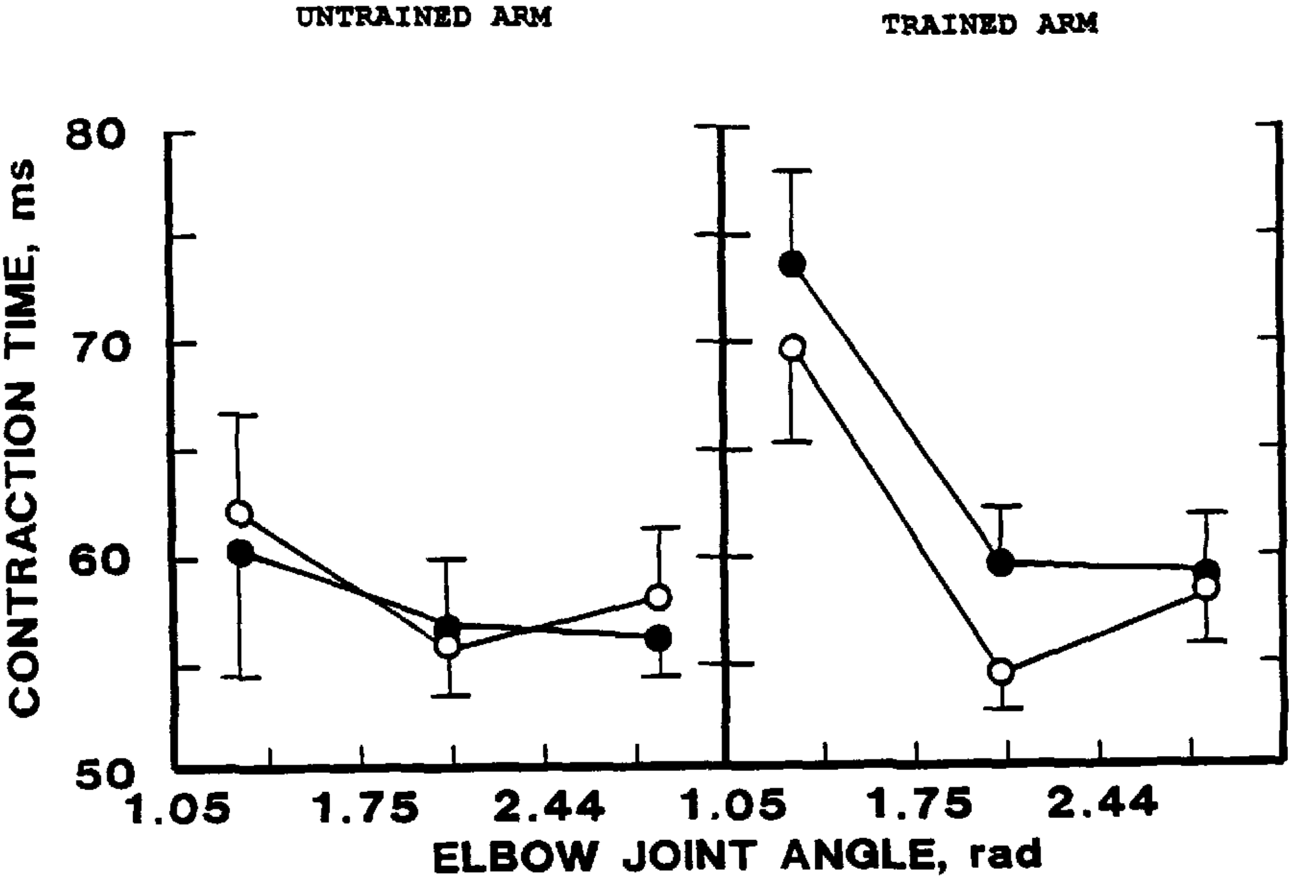

FIG.11. Contraction time during electrically evoked twitch contractions of elbow flexors of both arms before (open circles) and after (filled circles) training. *$P<0.05$, change after training.

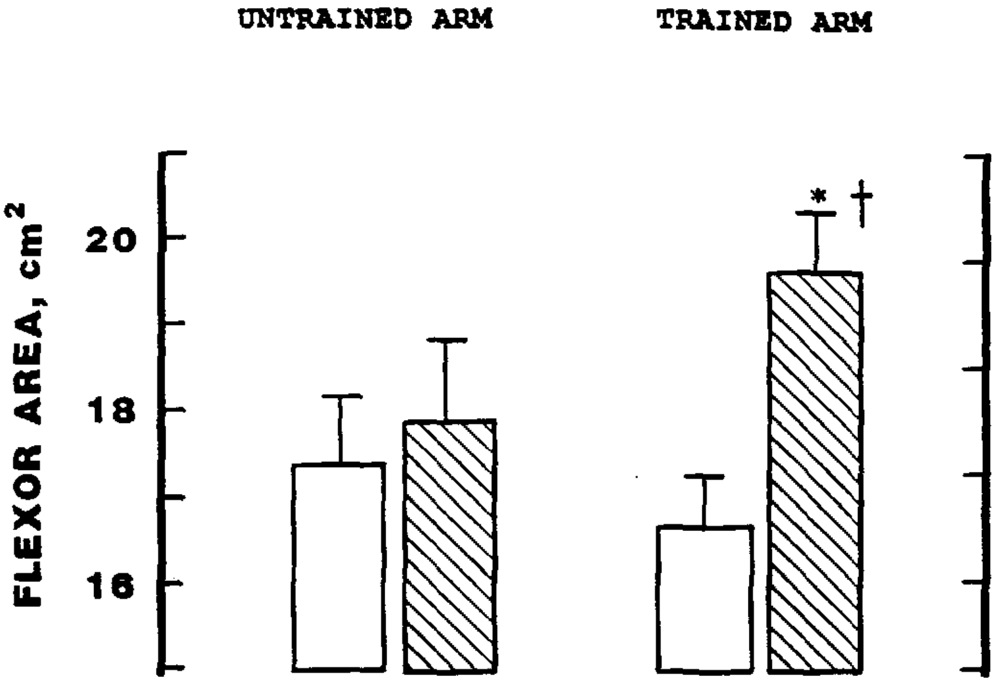

FIG.12. Maximal cross-sectional area of elbow flexors in trained and untrained arms before (open bars) and after (hatched bars) training. *P<0.001, difference between arms.

and that the extensors of both arms were trained during the bench press exercise. The cross-sectional area of the humerus did not change after training.

The flexor/extensor area ratio calculated for the arms did not change significantly during the investigation period even though the trained arm had a higher ratio than the untrained arm post training (.89 vs .76), ($p=.042$) whereas prior to training it did not (.79 vs .80)(Fig. 13).

Significant ($p<0.01$) increases in the cross-sectional area of the flexors (3.62 cm^2, 4.4%) and the extensors (6.9 cm^2, 9.9%) of the right leg but not the left leg were observed over the course of the study (Table vi, appendix c), despite the fact that both legs were trained simultaneously. A significant ($p<0.01$) increase in the area of the right femur was also noted.

3.4.1. MUSCLE FIBRE CHARACTERISTICS

In both arms type I and type II fibre area increased after training ($p<0.005$) (Fig.14). The type II fibre area increase in the trained arm (30.22%, 5617.0-7311.0 μm^2) was significantly ($p<0.05$) greater than in the control arm (10.7%, 5609.0-6209.0 μm^2). Type II fibre area increased more than type I, as indicated by a significant increase ($p<0.05$) in the FT/ST (II/I) area ratio of the trained arm (1.13 to 1.29) (Fig.14); there was no change in the control arm. The percentage of type I fibres in the trained arm was found to be initially different from that of the untrained arm (39.5% vs 45% respectively; $p<.035$), but this difference was not altered by training.

The relative (%) increases in elbow flexor 1 RM capacity did not correlate significantly with either muscle ($r=.0265$) or muscle fibre (type I $r= -.1438$, type II $r= -.2635$) hypertrophy.

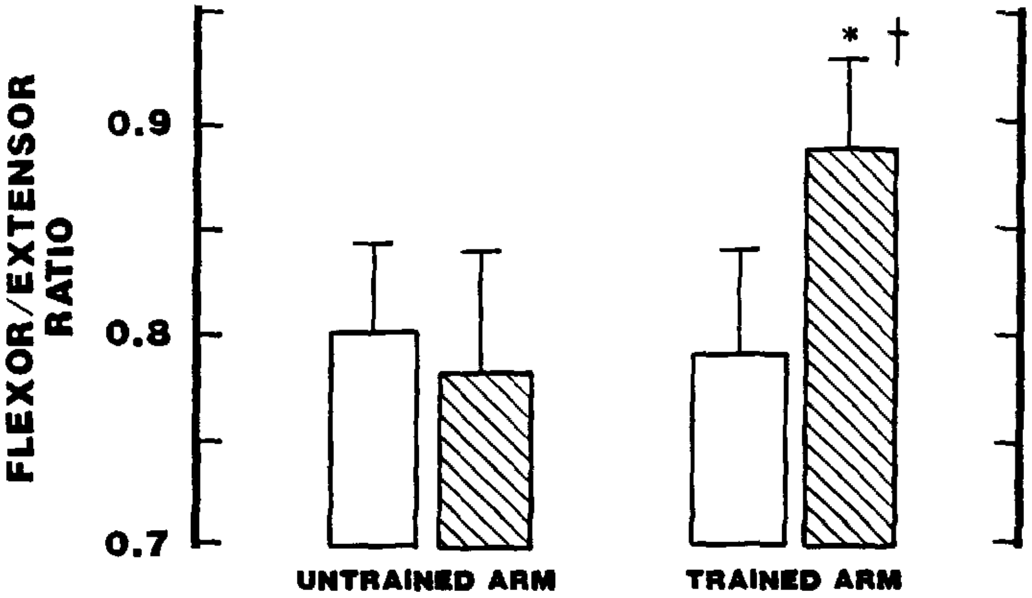

FIG. 13. Maximal flexor-to-extensor ratio in trained and untrained arms before (open bars) and after (hatched bars) training. $^*P<0.05$, change after training and $\dagger P<0.05$, difference between arms.

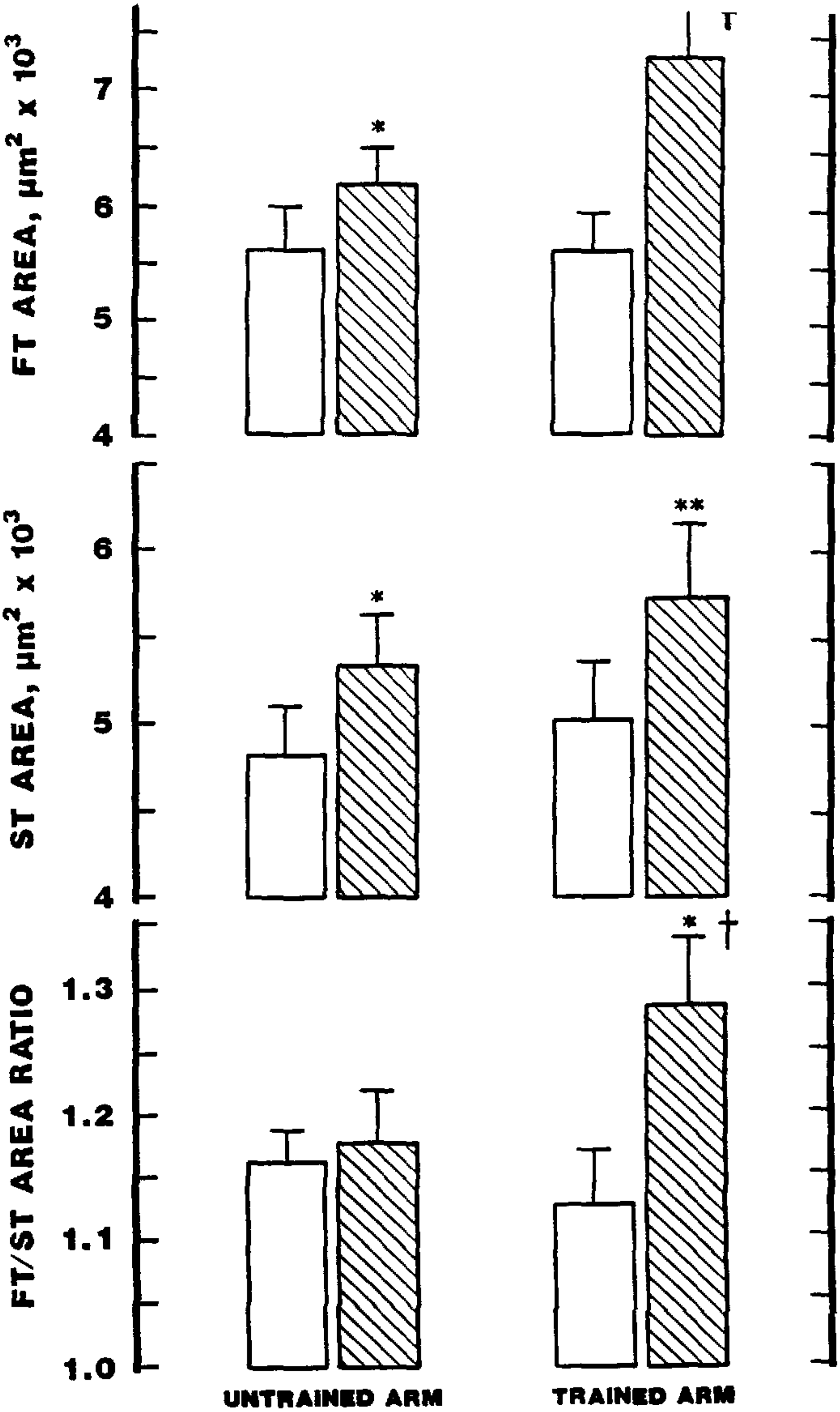

FIG. 14. Mean cross-sectional areas of type II (fast-twitch, FT; top) and I (slow-twitch, 5T; middle) fibres and FT-to-ST area ratios (bottom) in biceps brachii muscles of both arms before (open bars) and after (hatched bars) training. **P*<0.05, change after training (top & bottom); **P<0.001 and †*P*<0.001, greater increase in FT vs ST fibres in trained are (top). ***P*<0.01, change after training (middle); †*P*<0.05, difference between arms (bottom).

CHAPTER 4

DISCUSSION

All subjects were able to successfully complete the training without injury. Compliance was excellent; one subject missed a single session because of a prior commitment and another missed two sessions due to minor back pain sustained outside of training. Kaufman (1985), as part of his rationale for selecting the adductor digiti minimi as the muscle his subjects trained, cited the fact that older subjects find strength training more uncomfortable than young people. This was not the experience in this investigation as the subjects appeared to experience no greater discomfort than university aged subjects trained in a similar manner. It is encouraging that a training program involving large muscle groups is indeed viable and can be completed successfully by the elderly.

4.1. CHANGES IN MUSCLE PERFORMANCE AND MUSCLE SIZE

The major finding in the present study was that older men responded to weightlifting training in a qualitatively similar manner as young men, with large increases in the maximal load that could be lifted and accompanying enlargement of whole muscle and muscle fibre areas.

4.2.1. VOLUNTARY WEIGHTLIFTING STRENGTH

The pre-training 1 RM values were lower in the elderly subjects than the values recorded in a previous study in this laboratory involving untrained university males: (Bench Press (BP), 76%; Leg Press (LP), 86%; Arm Curl (AC), 62%; elderly subjects 1 RM values expressed as a percentage of the young subjects values,) but post-training the elderly subjects' 1 RM values were comparable to the initial levels of the young subjects (BP 97%, LP 106% and AC 89%)(unpublished data).

The improvement in dynamic strength represents a major finding of this study. Increases in BP (27%), LP (23%) and AC (49%) were equal to or greater than those reported in 19-21 yr old males following 10 weeks of strength training,(BP 16.5%, LP 23% and AC 18.9%, Wilmore, 1974). Moritani and de Vries (1980) reported an increase in the weightlifting capacity of elderly subjects' elbow flexors of 23% after 8 weeks of progressive weightlifting exercise and Aniansson and Gustafsson (1981) reported similar increases in the isokinetic torque of the knee extensors of elderly subjects after 12 weeks of training using body weight as resistance. A recent study by Frontera et al. (1988) provided the first evidence that older muscles could respond to intense resistance training with large increases in 1 RM performance concurrent with substantial whole muscle and individual muscle fibre hypertrophy. Data from the present study is in broad agreement with these findings, but the gains in muscle performance in this investigation were less for a greater degree of hypertrophy. (For a more complete discussion of hypertrophy see sections 4.3 and 4.4.) Frontera et al. (1988) reported an improvement of 107% in knee extensor 1 RM and 227% in the leg flexor 1 RM after 36 training sessions. These increases in lower limb voluntary strength are substantially greater than our increases in upper limb (BP, 27%, AC 49%) and lower limb strength (23%).

One possible explanation for the different findings is that leg extension and flexion exercises may not be as familiar to , or as comfortable for, the subjects to perform, as the leg press exercises, and as a result initial strength measures may be depressed due to discomfort or inhibition (Perrine & Edgerton, 1978). This may result in apparently large performance improvements as the subjects become familiar with the exercises through training. The 49% increase in AC strength in the present study was potentially inflated for similar reasons due to the nature of the arm curl training and testing device. The device had an unusual "sticking point" which possibly deflated pre-training values. With training, the subjects became accustomed to the leverage mechanism of the machine and this may have been reflected in the large increases in strength.

In addition to the substantial gains in the maximal weight lifting capacity in this study, there was a notable improvement in muscular endurance during repeated lifting. After training, subjects were able to lift their pre-training 1 RM from (range) 4 to 34 times in the trained arm and from 1 to 16 times in the untrained arm. By the seventh decade of life losses in strength and power often interfere with many common activities of daily living such as lifting and carrying, raising and lowering body weight and walking. It seems likely that increases in muscular endurance of the type reported here might enable seniors to accomplish certain tasks which may otherwise prove to be impossible or extremely fatiguing.

4.2.2. ISOKINETIC AND ISOMETRIC STRENGTH

The benefits of training were somewhat specific to the mode of exercise employed as strength performance measured on the training device increased far more than in the less familiar isometric and isokinetic tests. While there were no increases in isometric elbow flexor strength post training at any measured joint angle, there were significant increases in isokinetic bilateral leg press and unilateral arm flexion torque at all velocities tested. Most studies involving isokinetic measures have examined knee extension, and increases of 7 - 22% after a short period of training have been reported (Aniansson & Gustafsson, 1981, Aniansson et al., 1984). Similar increases of 17 - 18% were observed in the present study in which subjects trained using a bilateral leg press manoeuvre. As with the 1 RM measures, isokinetic strength gains were seen in both the trained and untrained arms. This was perhaps due to a neural transfer effect; for example, an enhanced ability of the central nervous system to recruit the motor units of the untrained arm as a result of the neural adaptations occurring in response to training in the trained arm. It is also possible that the elbow flexors of both arms received a moderate stimulus during the seated dead lift and bench press exercises.

The observed specificity points to the important role of nervous system adaptations in the response to strength training, in particular the role of learning and coordination (Rutherford & Jones, 1986). The implication for the design of strength training programs for the elderly is that the strength training exercises should simulate as closely as possible the most common strength-requiring tasks likely to be encountered by this population. Such an approach will ensure the best possible return on the training investment.

The lack of a significantly greater increase in isometric and isokinetic performance in the trained vs. the untrained arm was a puzzling finding, particularly in view of the fact that the trained arm underwent the greatest increase in muscle and muscle fibre cross-sectional area. A greater increase in strength would be expected to accompany a greater increase in muscle mass. Such a finding is not unique to the present study however. Frontera et al. (1988), found that right knee extensor muscles failed to increase in isometric strength despite an 11.9% increase in muscle cross-sectional area. In the left knee extensors the increase in isometric strength (7.7%) was slightly less than the increase in muscle size (9.3%). In other work by Dons et al. (1979), weight training in young men caused a greater increase in muscle cross-sectional area (10 - 17%) than isometric strength (4 - 5%). The authors also reported that weight-lifting performance increased 24 -42%. In a previous study in this laboratory (unpublished observations) a significant increase was not found in isometric strength after 5 months of weight training by young men despite significant increases in weight-lifting performance and muscle cross-sectional area. In addition, in a recent study no increase was found in the peak isometric force of overloaded rat soleus despite significant increases in muscle mass and muscle fibre area (Kandarian & White, 1989).

It is difficult to explain why any measure of strength would not increase if muscle size increased. Perhaps in the present study training caused a "negative" neural adaptation, which took the form of inhibition of the elbow flexors during isometric contractions, thereby preventing increased force despite hypertrophy. This explanation can be excluded because motor unit activation in the flexors was near maximal and similar before and after training. A counterproductive neural adaptation might have taken the form of increased co-contraction of antagonists; thus, increased cocontraction of triceps in the less familiar isometric task may have offset the increased contractile force of the agonists (elbow flexors). The present investigation has no data related to this possibility, but there is one report in the literature of greater co-contraction in the leg muscles of trained power athletes than endurance athletes (Osternig et al., 1986). In view of the many ways in which the muscles acting at the elbow joint can be activated and coordinated(Buchanan et al.,1989), such seemingly counterproductive adaptations cannot be ruled out.

Perhaps the observed hypertrophy did not increase the intrinsic force-generating capacity of the muscle. It cannot be argued that hypertrophy in these older muscles was entirely the result of connective tissue proliferation, because the increase in fibre size was at least equivalent to that of the whole muscle. Furthermore, the greatly hypertrophied muscle of bodybuilders shows no evidence of connective tissue proliferation (Sale et al.,1987). In the previously cited study of rat soleus (Kandarian & White, 1989), hypertrophy after 30 days of overload was not associated with connective tissue proliferation, an increase of interstitial fluid volume , or a decrease in protein content. These authors suggested that ultrastructural examination of the myofibrils and cytoarchitecture and assessment of possible alterations in the excitation-contraction coupling might help uncover the mechanisms responsible for the decrease in specific tension (i.e., the force developed per unit muscle cross-sectional area) that can accompany hypertrophy. Whatever the mechanisms, they may account for the pattern of results found in the present study.

A third possible explanation of these results involves the orientation of the arms during training and testing. The training of the elbow flexors was carried out with the humerus flexed at 45° into the frontal plane on a preacher style bench. Testing of the elbow flexors for 1 RM strength was carried out on the same apparatus, but for isometric MVC, interpolated twitch, electrophysiology and isokinetic testing the humerus was flexed 90° into the frontal plane. It could be that the change in the orientation of the arm during the testing of these latter measures from the position at which it was trained, may have been responsible for some of our findings or the lack thereof.

4.3. MUSCLE CROSS-SECTIONAL AREA

Voluntary strength gains were accompanied by increases in muscle cross-sectional area. The elbow flexor area of the trained arm in our subjects increased 17% in response to training after 12 weeks. Ikai and Fukanaga (1970) utilizing ultrasonic measuring devices to study the effects of 100 days of isometric training on muscle cross-sectional areas in young males reported increases of up to 23%. Though the increase in muscle cross-sectional area was smaller in the present investigation, the subjects trained for 36 as opposed to

100 sessions. Moritani and de Vries (1980) reported only a 1.5% increase in elbow flexor area in their 67 -72 year old subjects following 8 weeks of progressive resistance training. These authors employed a 4 site skinfold technique to estimate muscle area which assumes that no decreases in intramuscular fat deposits or changes in connective tissue result from training. Such changes occurring in combination with muscle fibre hypertrophy could result in increases of muscle cross-sectional area undetected by this technique.

Recently Frontera et al. (1988) found a 10 - 11% increase in quadriceps cross-sectional area in response to heavy resistance training in older males and while this represents a smaller increase than found in the present investigation, this may simply reflect the greater hypertrophy potential of the arms versus the legs. Previous investigations from this laboratory in experienced weight-trainers suggest that the arms possess a significantly greater potential for hypertrophy than the legs (Sale & MacDougall, 1984). The lesser overall hypertrophy of the knee extensors in the present study (1.5 to 9.9%) compared to the arms seems to support this hypothesis.

A notable observation in the present study is that muscle size increased significantly only in the right knee extensors and flexors even though both legs were trained simultaneously in a bilateral leg press movement. Perhaps most of the subjects were right limb dominant and unintentionally favored this limb during training. Leg extensor muscle CSA increases of 9.9% are comparable to extensor muscle increases noted by Frontera et al. (1988).

4.4. MUSCLE FIBRE CROSS-SECTIONAL AREA

In the present study, increases in the cross-sectional area of the elbow flexors were associated with corresponding muscle fibre area increases. While type I and II fibres from both arms increased signifcantly, the substantial 30% increase of type II fibres in the trained arm is of particular note and may perhaps account in large part for the strength gains in that arm. In addition, the increase in the maximal evoked elbow flexor torque seen post training could also be explained by the fibre hypertrophy. Fibre area increases in this study were greater than those reported by Aniansson and Gustafsson (1980) (5 - 9%, not significant) in the vastus lateralis of 69 - 74 year old men after 12 weeks of training, but not as great as those reported by Larson (1982) (38 - 51%) utilizing the "lesser fibre diameter" method. Frontera et al. (1988) found comparable increases of 27.5% in type II fibre areas but larger increases in type I area (33.5 vs 13.7%) than in the present study. Fibre type distribution was not affected by training.

Moritani and deVries (1980), based on muscle cross-sectional area estimates and IEMG data, concluded that the increases in strength displayed by the elderly in response to training are the result of neural factors. In the present study, the significant increases in muscle and muscle fibre areas, together with the impressive gains in voluntary strength measures indicate that hypertrophy as well as neural factors can contribute to enhanced strength in the elderly.

4.5. ELECTROPHYSIOLOGICAL PROPERTIES

4.5.1. PEAK TWITCH TORQUE

An increase in muscle cross-sectional area after training should theoretically result in a greater force production during electrically evoked activation. Bodybuilders and weightlifters do have greater evoked twitch force than untrained men (Sale et al.,1983); however, short term studies of strength training in young subjects have noted gains in maximum voluntary strength with no corresponding increases in the evoked maximal twitch and tetanic tensions (Davies & Young, 1983;

McDonagh et al., 1983). Cross-sectional studies of the ankle plantarflexors in men aged 69-100 years have reported age-associated reductions in maximum twitch torque and in the rate of torque development (Davies & White,1983; Vandervoort & McComas,1986), but the effects of strength training on muscle contractile properties in the elderly have not been investigated.

In the present work, significant increases in peak twitch torque were seen at elbow joint angles of 120 and 165° in the trained arm. This is consistent with the finding of increased muscle and muscle fibre cross-sectional area. Although there was an increased torque at the greater joint angles, there was no change at 75°. It could be that because of the short duration of the twitch contraction, the relatively greater amount of series elasticity that exists at the smaller joint angles cannot be taken up quickly enough to enable the muscle to achieve its full contractile tension. As a result, it may be possible for a muscle to become stronger as a result of training, but not display any greater evoked torque production at smaller joint angles.

In the untrained arm an increase in twitch torque was noted at an angle of 165°. This was unexpected since the arm was not trained; however, an increase in muscle fibre cross-sectional area was noted and this may perhaps account for the increased twitch torque. However, if this significant increase in fibre area was the mechanism responsible for increased twitch torque at 165° then a similar type of increase in twitch torque would be expected at a joint angle of 120°. This did not occur and in fact significant decreases in twitch torque were noted at this angle post-training. Since the other electrophysiological measures were based upon the same twitch contractions as these torque measurements and were also a result of them, (that is, a decreased twitch torque would ordinarily result in a decrease in the time to peak torque, half relaxation time and decreased rates of torque production), the results in these other parameters are similarily affected at this joint angle. No change was noted in twitch torque at a joint angle of 75°.

Since twitch torque increased in the trained arm at two of three joint angles tested and also at one of the joint angles in the untrained arm, no convincing evidence exists of a systematically greater increase in twitch torque in the trained arm. These results are consistent with the lack of a greater voluntary isometric strength increase in the trained arm. Of the previously discussed mechanisms that might account for the failure of voluntary isometric strength to increase despite hypertrophy, only the possible decrease in specific tension can be offered to explain the failure of twitch torque to increase more in the more hypertrophied trained arm. A greater degree of hypertrophy than that observed in the present study may be necessary before absolute muscle force begins to increase.

4.5.2. MAXIMUM RATE OF TORQUE DEVELOPMENT

The maximum rate of torque development was significantly higher in the trained arm at a joint angle of 165° post-training. As there was no change in the time to peak torque, the maximum rate of torque production must increase if peak torque increases.

An increased maximum rate of torque production may also suggest that strength training, by causing the selective hypertrophy of fast twitch muscle fibres, produced a faster contracting muscle. If this was the case, similar increases in rates of torque production should have been noted at the other joint angles, which it was not. It may be that by extending the arm to 165°, the series-elastic component of the muscle is taken up to such an extent that the muscles rate of torque development is increased and this, combined with a possibly stiffer muscle post training, produces a quicker contraction in response to the twitch stimulus.

4.5.3. HALF RELAXATION TIME.

There was a significant increase in half-relaxation time in the trained arm at all joint angles tested post training and this is in agreement with similar observations in young adults after strength training (Kitai & Sale, 1989). The increase in half-relaxation time contributed to the increase in the torque-time integral. The prolongation of the twitch contraction would shift the force-frequency relation to the left, thereby allowing maximal tetanic tension to be achieved at a lower motor unit firing frequency. This adaptation coupled with the already observed slowing of older muscles even without training (Vandervoort & McComas, 1986) should allow strength-trained seniors to achieve maximal force at lower motor unit firing rates than their younger counterparts. Lower firing rates might also increase resistance to fatigue.

4.6. MECHANISMS FOR INCREASES IN MUSCLE PERFORMANCE

Despite the evidence for hypertrophy in the present study, it is unlikely that all of the gains in voluntary performance could be attributed to that mechanism. In agreement with the work of others (Rutherford & Jones, 1986), the greatest gains were manifest on the training apparatus, indicating a specificity effect. During elbow flexion with the trained arm, the 48% improvement in 1 RM load was accompanied by a corresponding average increase in isokinetic torque at the five angular velocities of only 8.8% and there was no change in isometric MVC. This variability resulted in the maximal force per unit cross-sectional area increasing by 27% in dynamic exercise, but decreasing by 7% and 13% in isokinetic and isometric tests respectively. Many other investigators have reported training-induced alterations in muscle performance which could not be explained by accompanying changes in muscle area (Ikai & Fukunaga, 1970; Komi et al., 1978; Costill et al., 1979; Dons et al., 1979; Moritani & deVries, 1980; Young et al., 1983; Jones & Rutherford, 1987).

The most likely explanation for the largest increases occurring during testing on the training apparatus is that some of the improvement was due to a learning effect, or to neural adaptations which optimized force generation. In a study by Rutherford and Jones (1986), weightlifting training resulted in a 200% increase in training weights but only a 15 to 20% gain in isometric strength. It was concluded that much of the improvement in dynamic lifting could be attributed to an enhanced contribution of other muscle groups involved in the activity. Other workers have postulated that strength gains in the absence of hypertrophy and increases in the strength of the control limb are evidence for neural adaptations to resistance training (Moritani & deVries, 1980). Some of these observations may help to explain the variable increases in performance in the present study. That subjects become more comfortable with the training apparatus over the course of the study is very probable; a 12.7% increase in the 1 RM capacity of the control arm was observed. One somewhat puzzling observation, however, was that substantial muscle hypertrophy without a significant increase in evoked twitch torque was noted in the subjects, even though their ability to recruit motor units was apparently maximal both before and after training, at least in the isometric test. Despite this, subjects demonstrated minimal increases in performance except on the training apparatus. This finding has important implications for health care practitioners involved in therapeutic exercise programmes. It may be incorrect to assume that gains in muscle strength and size will translate into improved function in the physically arduous tasks of daily living. The best results would probably be obtained from training programmes that mimicked actual activities as closely as possible.

SUMMARY AND CONCLUSIONS

In summary, this work has demonstrated that aging muscle is able to respond to progressive overload weight lifting training in a qualitatively similar manner as the muscles of young healthy individuals. Large increases in strength are mediated by an increased whole muscle cross-sectional area, particularly the area of the type II fibres. The effects of weight lifting training carry over somewhat to isokinetic power production, but do not result in an enhancement of isometric strength. An additional important finding was that following the training, subjects were able to perform many repetitions of an exercise with a load that corresponded to their initial 1 RM; thus there were major improvements in high strength endurance capacity. It seems likely that such notable gains in strength, power and endurance in seniors would translate into an improved function in many activities of daily living which may otherwise prove difficult.

These findings suggest that exercise practitioners should utilize weight lifting as a recommended mode of training in older subjects. It must be remembered however that many of the middle-aged and elderly have covert heart disease and hypertension on exercise. Further study is needed to investigate the safety of weight lifting training in seniors. Until such time as the results become available, exercise practitioners must insist on a rigorous physical examination of any older individual who wishes to engage in a weight lifting programme, and carefully monitor heart rate, heart rhythm and arterial blood pressure during the activity.

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APPENDIX A

Positive adaptations to weight-lifting training in the elderly

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BROWN, ALLAN B., NEIL MCCARTNEY, AND DIGBY G. SALE. *Positive adaptations to weight-lifting training in the elderly.* J. Appl. Physiol. 69(5): 1725–1733, 1990.—Maximal weight-lifting performance, isometric strength, isokinetic torque, whole muscle and individual fiber cross-sectional areas, and muscle evoked contractile properties were assessed in 14 elderly males before and after 12 wk of weight-lifing training. Dynamic elbow flexion training of one arm resulted in a significant 48% mean increase in the maximal load that could be lifted once (1 RM) and a smaller improvement in isokinetic torque (8.8%) but no change in isometric strength. In the contralateral control arm, 1 RM and isokinetic torque increased by 12.7 and 6.5%, respectively, but isometric strength did not change. The interpolated twitch technique confirmed complete motor unit activation during a maximal isometric contraction of the elbow flexors before and after the training. Bilateral leg press training effected mean increases of 17 and 23% in isokinetic torque and dynamic lifting capacity, respectively. The mean maximal cross-sectional area of the elbow flexors (biceps brachii and brachialis) increased by 17.4% in the trained arm but did not change the control arm. The increase in the mean area of type II fibers in the biceps brachii muscle in the trained arm (30.2%) was greater than the corresponding change in the control arm (10.7%, $P < 0.05$). The most significant change in the evoked contractile properties of the trained elbow flexors was the increase in twitch half-relaxation time. It is concluded that older individuals retain the potential for significant increases in strength performance and upper limb muscle hypertrophy in response to overload training.

strength training; contractile properties; hypertrophy

SKELETAL MUSCLE STRENGTH has been found to increase up to 30 yr of age, to plateau until ~50 yr, and to decline slowly thereafter (19). In older individuals, peripheral muscle weakness may compromise common activities of daily living, such as rising from a low chair or lavatory seat (38), and may lead to dependency on others. The relative contributions of changes in the neuromuscular system and progressive inactivity to the reduction in strength with aging are unclear.

The maximal cross-sectional area of the quadriceps muscles may be 25% lower in the eighth decade than in the third decade (39). This decrease has been attributed to small reductions in the size of type II fibers (13) and to a progressive loss in the total number of muscle fibers (21, 22), particularly the type II moiety (19, 20). Evidence from electrophysiological studies indicates that the loss of the type II fibers is secondary to motoneuron cell death (6); the fiber type grouping and enclosed fibers that are seen in histological sections of older muscles lend support to this finding (13). Based on the similar reductions in muscle mass and strength with aging and evidence for the preservation of specific tension in muscle, Grimby and Saltin (14) have suggested that quantitative rather than qualitative changes within muscles account for most of the strength loss.

The extent to which reductions in strength with aging may be overcome by appropriate physical training is uncertain. There are relatively few published studies on the effects of strength training in the elderly, and in most of these isometric training of very small muscle groups (17) or calisthenics and elastic bands (2, 3) have been used rather than progressive resistance training. Variable increases in strength have occurred after all forms of training, but the greatest gains were reported recently by Frontera and colleagues (11). These investigators noted increases of >100% in the strength of the knee extensors and flexors after 12 wk of weight-lifting training, along with evidence of considerable muscle hypertrophy. This is in contrast to other short-term studies of strength training in the elderly, which have demonstrated gains in the strength of knee extensors (3) and elbow flexors (28) with little or no evidence of muscle hypertrophy, suggesting that the improvements were due to neural adaptations.

The present work was designed to extend previous observations by investigating the effects of strength training on muscle strength, whole muscle and muscle fiber cross-sectional areas, muscle contractile properties, and the completeness of motor unit activation in older men.

METHODS

Subjects. Fourteen healthy 60- to 70-yr-old male volunteers took part in this study (means ± SD: age 63 ± 2.7 yr, height 174 ± 5.5 cm, weight 79 ± 7.7 kg). None had prior experience with weight-lifting training. All subjects gave their informed consent, and the study was approved by the appropriate Institutional Review Committee. Before acceptance into the study subjects performed a progressive incremental cycle ergometer test (15) to detect any signs of latent heart disease or severe pulmonary impairment; such individuals were excluded from the study.

Study design. The study was designed so that the subjects would specifically train the elbow flexors of one arm only ("trained" arm), affording a within-subject control and thus reducing the need for a control group of subjects. It should be emphasized, however, that although the "untrained" control arm did not receive specific elbow flexion training on the device to be described below, it was involved in two other exercises (bench press

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and seated dead lift) that would have provided a mild training stimulus to the elbow flexors. The training regimen incorporated additional arm, leg, and trunk exercises to provide an overall conditioning stimulus. Posttraining, changes in weight-lifting capacity were evaluated in all the arm and leg exercises but not in movements primarily involving the trunk.

Training. Training was done on 3 alternate days each week for 12 wk. Bilateral leg press, supine bench press, and seated dead lift exercises were done on a multistation weight-lifting machine (Global Gym, Downsview, Ontario, Canada); bent-leg abdominal curls were performed on a padded station on the floor. One arm was selected at random, and the elbow flexors were trained on a custom-built weight-lifting apparatus (Rubicon Industries, Stoney Creek, Ontario). Exercises were done in a circuit set system, with 2-min pauses between sets. Each set comprised 10 repetitions in bench press and arm curl exercise, 15 repetitions in leg press, and 12–20 repetitions in the seated dead lift and abdominal curl exercises. The bench press was performed supine as a repeated bilateral arm press exercise from an initial position close to the chest. For the arm curl exercise the subjects were seated and began the movement with the arm in a fully extended position with the palm facing up. The elbow was flexed through a full range of movement to lift the weight before being returned to full extension. The bilateral leg press exercise was performed in a seated position with the back fully supported and the feet resting on a footplate. The exercise consisted of simultaneous hip and knee extension and ankle plantar flexion. Subjects began the movement with the knees flexed at 90° and then lifted the weight by straightening the legs before resuming the starting position. Training progressed from two sets of each exercise at 50% of the initial one-repetition maximum (1 RM) to four sets at 70–90% of 1 RM over the course of the study. Throughout the training program the weights were adjusted to restrict the number of repetitions in each set to the required number.

Measurement of voluntary strength, torque, and weight-lifting capacity. Weight-lifting capacity was measured as the heaviest weight that could be lifted once throughout the complete range of movement (1 RM). Testing took place on 2 separate days, and the heaviest weight lifted was recorded as the pretraining value. The movements tested were unilateral arm curl, bilateral leg press, and supine bench press. After the training program, the 1 RM was again determined, and in addition each subject did as many repetitions as possible with the pretraining 1 RM to provide a measure of endurance. In this endurance test, repetitions were done at a rate of 10/min, the same rate used in the training.

Maximal concentric contraction torque of the elbow flexors was measured on a Cybex isokinetic dynamometer (Lumex, Ronkonkoma, NY) before and after the training period. Unilateral elbow flexion was performed at angular velocities of 0.52, 2.09, 3.14, 4.19, and 5.24 rad/s (30, 120, 180, 240, and 300°/s) in random sequence. For each contraction, peak torque was taken as the highest value attained regardless of where it occurred in the range of movement. The best performance of three trials at each velocity was recorded as the maximal value. Bilateral leg press (simultaneous hip and knee extension and ankle plantar flexion) torque was measured as described in detail previously (37). Briefly, a leg press apparatus was coupled to a Cybex dynamometer, and the resulting 4:1 gear reduction enabled the Cybex to accommodate the large torques that can be generated in a bilateral leg press maneuver. However, because this arrangement also restricts the maximal angular velocity of the instrument's lever arm to 1.31 rad/s (75°/s) compared with the usual 5.24 rad/s (300°/s), measurements were recorded during three trials at lever arm angular velocities of 0.26 and 1.31 rad/s. The maximal voluntary isometric strength of the elbow flexors of each arm was measured on a custom-built apparatus as described in detail elsewhere (25). Subjects did two maximal voluntary contractions (MVCs) separated by 2 min of rest at joint angles of 1.31, 2.09, and 2.88 rad (75, 120, and 165°); the order of testing was selected at random, and the highest torque in the two trials was recorded as the maximal value.

Motor unit activation. The extent of motor unit activation during the MVCs was assessed using the interpolated twitch technique as described by Belanger and McComas (4). A supramaximal electrical stimulus was delivered to the involved muscles during the MVCs. If an increment occurred on the MVC torque recording, the magnitude of the increment, expressed as a percentage of the maximal twitch magnitude evoked at rest, represented that portion of the muscle mass not activated by the voluntary effort. The method cannot distinguish between incomplete recruitment or insufficient motor unit firing rate as being responsible for the increment on the torque recording; hence the term activation is used (4). Therefore complete activation, as indicated by no increment on the torque recording, implies that all motor units have been recruited and are firing at rates sufficient to produce maximal tetanic force.

Measurement of evoked muscle contractile properties. The evoked contractile properties of the elbow flexors were determined in each arm by use of the same apparatus and joint angles previously employed for the measurement of isometric MVC. The assessment of evoked twitch torque always preceded the testing of isometric MVC to obviate the potentiation of the twitch by a maximal effort (36). Twitch contractions were evoked by percutaneous nerve stimulation as described in detail previously (25). Briefly, the contractions were evoked by percutaneous electrical stimulation via two lead plate electrodes, which were encased in moistened gauze impregnated with conducting medium. One electrode was placed on the motor point of the biceps, and the other was placed on the ventral surface of the forearm just below the elbow. The latter placement ensured stimulation of brachioradialis and brachialis as well as biceps. Stimuli were rectangular voltage pulses of 50- or 100-μs duration, delivered by a Devices stimulator (Medical Systems). When no further increases in torque could be produced by additional increases in the stimulus intensity, the twitch contraction was considered to be maximal. The data were displayed on a storage oscilloscope (Hewlett-Packard 120 1B) and analyzed on-line by use of a laboratory computer (PDP 11-03, Digital Equipment). Measurements included maximal twitch torque, contraction time, half-relaxation time, maximal rates of torque development and relaxation, and torque-time integral.

Measurement of muscle size. The cross-sectional areas of the flexors and extensors of the elbows and knees were measured from computerized tomography scans as reported previously (24). Included in the flexor compartment of the arm were biceps brachii and brachialis but not brachioradialis; the arm extensors were triceps brachii. The knee extensor compartment comprised the four quadriceps heads, and the knee flexor compartment also included the adductor muscles. The legs were scanned simultaneously at a point corresponding to 50% of the upper leg length as measured from the head of the fibula up to the lateral point of the greater trochanter. The arms were scanned individually at a point corresponding to 40% of the upper arm length up from the lateral epicondyle of the humerus to the acromium process.

Measurement of the muscle fiber characteristics. Muscle fiber characteristics of the biceps brachii muscle (long head) in both the trained and untrained arms were determined from percutaneous needle biopsy samples using established procedures (24). Measurements comprised fiber type distribution and the mean cross-sectional areas of type I (or slow-twitch, ST) and II (or fast-twitch, FT) fibers.

Statistical analyses. Descriptive statistics included means ± SE. Overall training effects were evaluated by analysis of variance techniques; specific differences were tested using the Tukey *A* method. The critical level for statistical significance was established at $P = 0.05$.

RESULTS

All subjects were able to successfully complete the training without injury.

Weight-lifting capacity. The 1 RM loads in all three weight-lifting exercises increased significantly ($P < 0.001$) after the training (Figs. 1 and 2). The single arm curl 1 RM was higher in both arms after the training ($P < 0.05$), but the mean increase in the trained arm (48.4%) was greater ($P < 0.05$) than the increase in the control arm (12.7%; Fig. 2). In addition, the absolute endurance was substantially increased after the training, inasmuch as subjects were able to lift their pretraining 1 RM an average of 7–19 times in the trained limbs and 7 times in the control arm (Table 1).

Isokinetic torque. The maximum isokinetic torque in bilateral leg press exercise performed at 0.26 and 1.31 rad/s increased by 17 and 18%, respectively, after the training (Fig. 1). During elbow flexion at the five angular velocities, the mean gains in the trained arm (8.8%, $P < 0.01$) were similar to those in the control arm (6.5%, $P < 0.01$; Fig. 3).

Isometric strength. During maximal isometric contractions of the elbow flexors, torque measurements demonstrated the well-established variation with joint angle, but there was no significant change in the maximum torque in either arm after the intervention period (Fig. 3). The failure of an interpolated stimulus to produce additional isometric torque confirmed that the subjects were able to achieve complete motor unit activation (98%) both before and after the training.

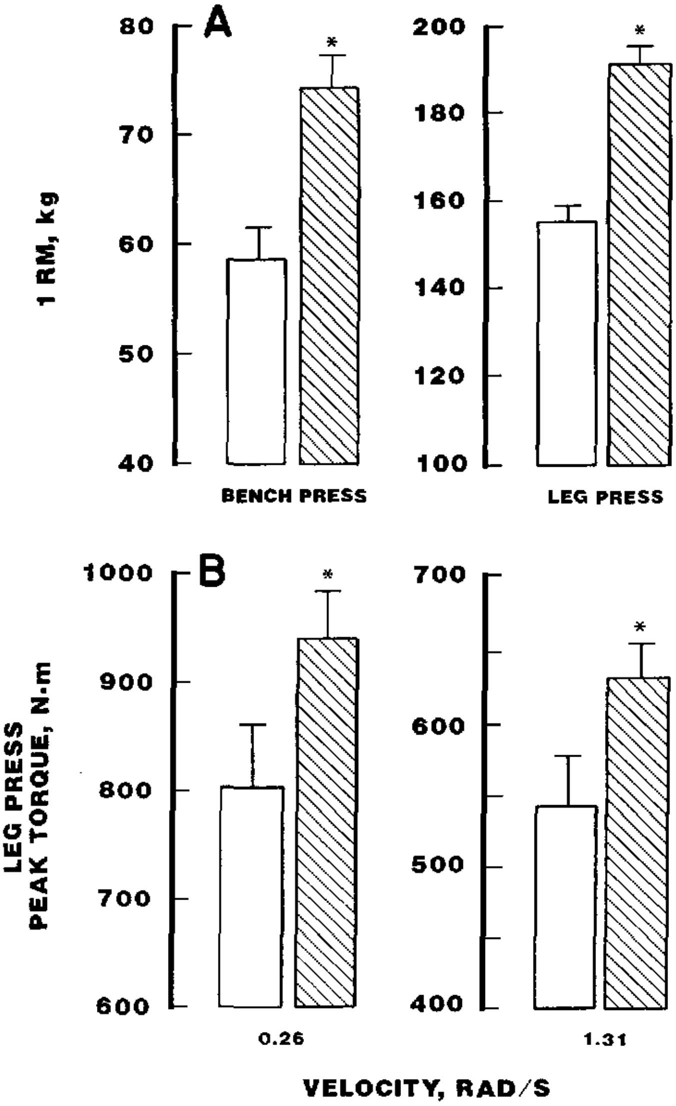

FIG. 1. *A*: maximal (means ± SE) weight-lifting capacity (1-repetition maximum, 1 RM) in bench press and bilateral leg press exercises, measured before (open bars) and after (hatched bars) 12 wk of training. *B*: maximal (means ± SE) isokinetic leg press torque at 2 angular velocities before and after training. * $P < 0.001$, increase with training.

Evoked muscle contractile properties. After training, increases in the maximal evoked twitch torque were recorded at elbow joint angles of 2.09 (9.1%) and 2.88 rad (11.6%) in the trained arm and at 2.88 rad (11.9%) in the untrained arm ($P < 0.05$; Fig. 4); there was also a significant decrease ($P < 0.05$) in evoked twitch torque in the untrained arm at 2.09 rad (11.2%). The twitch torque-time integral increased significantly ($P = 0.007$) in the trained arm after training at elbow joint angles of 2.09 and 2.88 rad, but there was no change in the control arm (Fig. 4). The maximal rate of torque development decreased ($P < 0.05$) in the untrained elbow flexors at the 2.09-rad angle and increased significantly ($P < 0.05$) in both arms at the 2.88-rad position, but there was no change at the other joint positions (Fig. 5). The times to attain peak twitch torque (Fig. 6) and the maximal rates of torque relaxation (Fig. 5) were similar in both arms

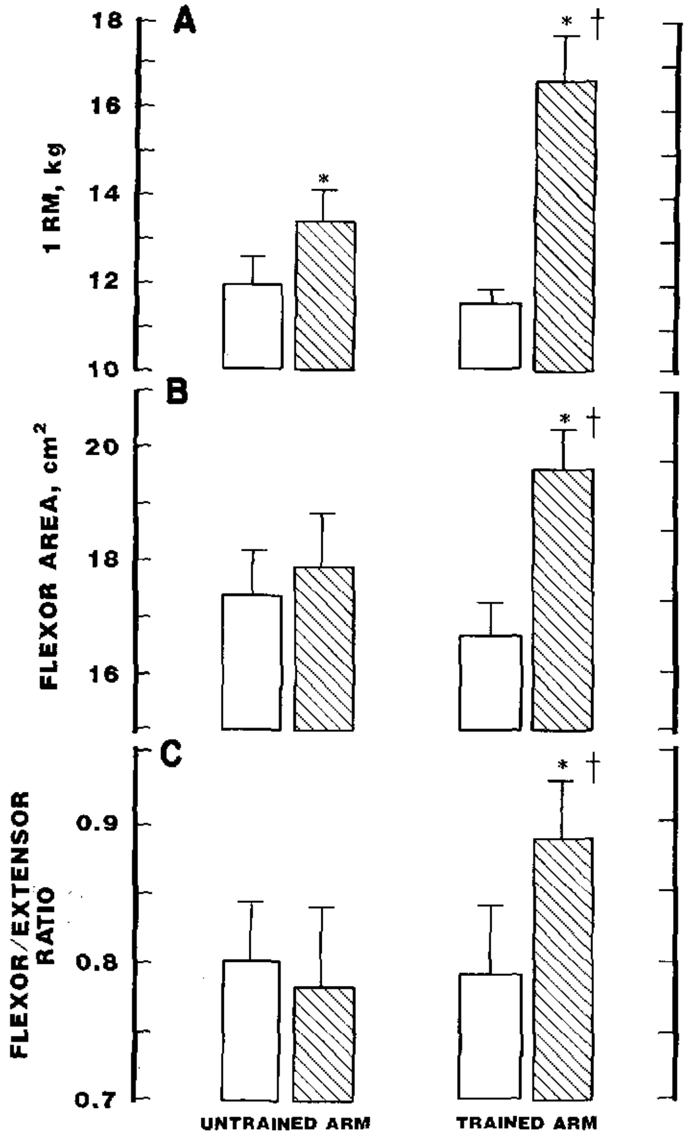

FIG. 2. Maximal weight-lifting capacity (1-repetition maximum, 1 RM, *A*), maximal cross-sectional area of elbow flexors (*B*), and flexor-to-extensor area ratio (*C*) in trained and untrained arms before (open bars) and after (hatched bars) training. * $P < 0.05$, change after training (*A* and *C*); * $P < 0.001$ (*B*) and † $P < 0.05$ (*A–C*), difference between arms.

TABLE 1. *Number of repetitions that could be completed by subjects after training with a load corresponding to their pretraining 1 RM*

Exercise	No. of Repetitions	
	Range	Mean
Bench press	5–10	7.0
Leg press	10–34	19.0
Arm curl		
Trained	4–22	14.0
Untrained	1–16	7.0

before and after the training. The half-relaxation times were greater in the trained arm at all joint angles after training ($P < 0.05$) and remained unchanged in the control arm (Fig. 6).

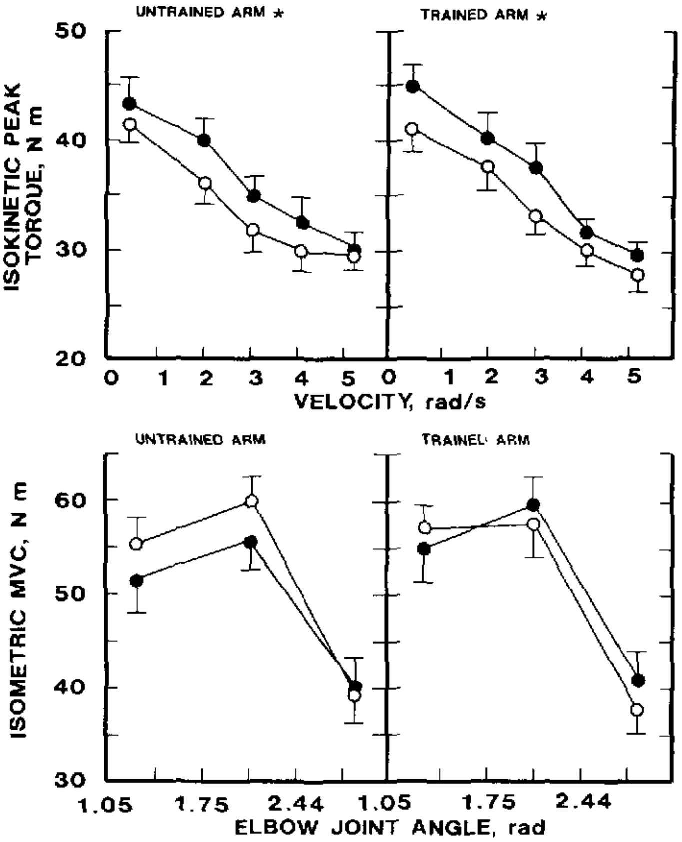

FIG. 3. Maximal isokinetic (*top*) and isometric torque (maximum voluntary contraction, MVC; *bottom*) during elbow flexion exercise in both arms before (open circles) and after (filled circles) training. * $P < 0.01$, overall increase after training.

Muscle cross-sectional area. Training resulted in an increase of 17.4% (16.7 to 19.6 cm^2; $P < 0.001$) in the mean maximal cross-sectional area of the elbow flexors in the trained arm but no change in the control arm (Fig. 2). In contrast, there was a small but significant ($P = 0.035$) increase in the maximal cross-sectional area of the elbow extensors in the control arm (22.1 to 23.7 cm^2) but less of a gain in the trained arm. It should be noted that the term "trained" refers only to the elbow flexors, because the elbow extensors of both arms received a training stimulus from the bench press exercise.

Before training the flexor-to-extensor area ratio was similar in both arms (0.79 and 0.80), but after training the ratio was higher ($P = 0.042$) in the trained arm (0.89) than in the control arm (0.76; Fig. 2).

There were significant ($P < 0.01$) increases after training in the mean maximal cross-sectional areas of the knee flexors (3.6 cm^2, 4.4%) and extensors (6.9 cm^2, 9.9%) in the right leg only despite the fact that both legs were trained simultaneously in bilateral movements.

Muscle fiber characteristics. After training, there was a significant ($P < 0.005$) increase in the mean cross-sectional areas of both type I (ST) and II (FT) fibers from the biceps brachii muscle of each arm (Fig. 7). However, mean type II fiber area increased more in the arm that received the more direct training stimulus (trained arm, 30.2%, $P < 0.05$) than in the less directly trained arm (untrained arm, 10.7%; Fig. 7). Type II fiber area in the trained arm increased more than type I area; consequently, there was a significant ($P < 0.05$) increase in

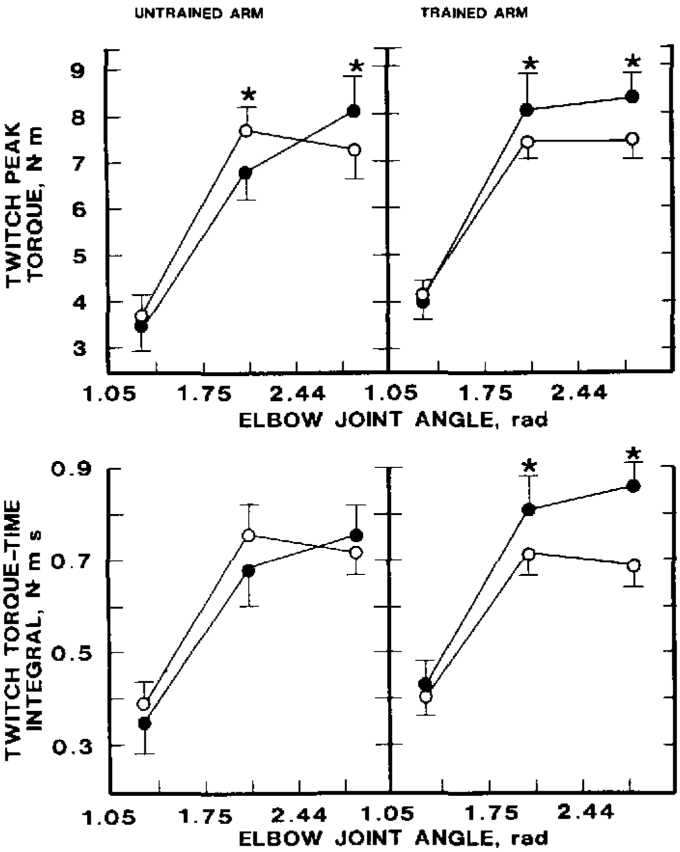

FIG. 4. Maximal twitch torque (*top*) and torque-time integral (*bottom*) during electrically evoked contractions of elbow flexors of both arms before (open circles) and after (filled circles) training. * $P < 0.05$ (*top*) and * $P = 0.007$ (*bottom*), change after training.

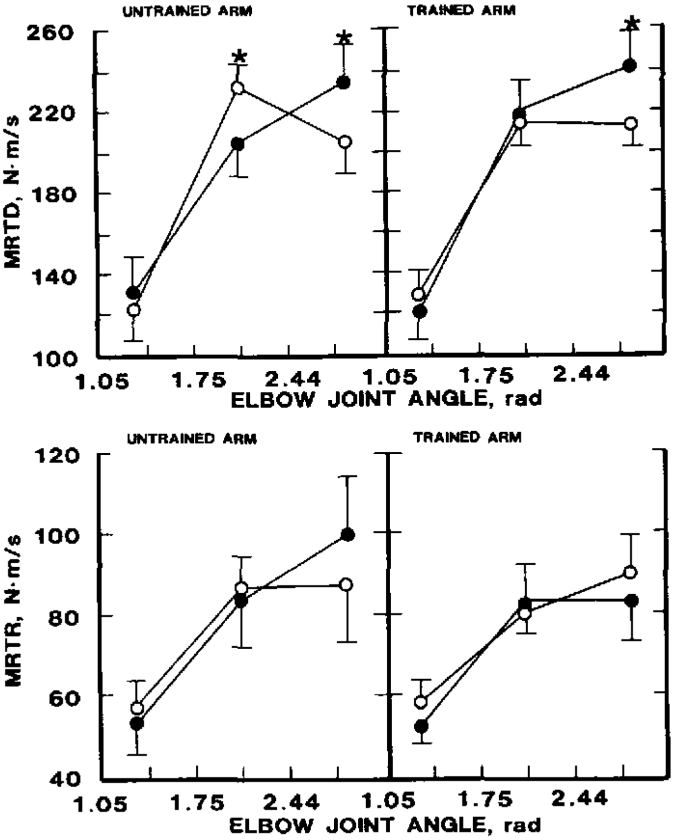

FIG. 5. Maximal rates of torque development (MRTD; *top*) and relaxation (MRTR; *bottom*) during electrically evoked twitch contractions of elbow flexors of both arms before (open circles) and after (filled circles) training. * $P < 0.05$, change after training.

the type II-to-I (FS-to-ST) area ratio (1.13 to 1.29). In contrast, the FS-to-ST area ratio did not increase significantly in the untrained arm (Fig. 7). The percent distribution of type I fibers in the biceps muscles of both the trained (40%) and untrained arm (45%) remained constant.

DISCUSSION

Changes in muscle performance and muscle size. The major finding in the present study was that the older men responded to weight-lifting training in a qualitatively similar manner as young men, with large increases in the maximal load that could be lifted and accompanying enlargement of whole muscle and muscle fiber areas.

Previous studies of strength training in the elderly have produced conflicting results. Moritani and deVries (28) reported an increase in weight-lifting capactiy of the trained elbow flexors of 23% but no change in upper arm girth after 8 wk of progressive weight-lifting exercise. Aniansson and Gustafsson (2) found a similar increase in isokinetic torque of the knee extensors and no significant increment in the cross-sectional areas of individual muscle fibers after 12 wk of training with body weight as resistance. In contrast, a recent study by Frontera et al. (11) was the first to show that older leg muscles could respond to intense resistance training with significant increases in muscle and muscle fiber size. Now the present study has shown that older arm muscles can also hypertrophy in response to strength training.

The latter two studies showed a similar general pattern of results. There was a very large increase in weight-lifting performance, a much smaller and sometimes insignificant increase in less specific isometric and isokinetic tests, and increases in muscle and muscle fiber size that were considerably smaller than the increases in weight-lifting performance but were similar to or moderately greater than the increases in the less specific performance measures.

However, there were notable differences between the two studies. Frontera et al. (11) found a much larger increase (107 vs. 48%) in weight-lifting performance, but we found a slightly greater increase (17.4 vs. 11.9%) in muscle cross-sectional area. Whereas a similar increase in type II fiber area was found in both studies (our study 30%, Frontera et al. 27.6%), a larger increase in type I fiber area was found by Frontera et al. (33.5%) than by us (13.7%). Thus our data gave the commonly observed pattern of greater hypertrophy of type II fibers and consequently an increase in the type II-to-I area ratio (7, 23, 34), whereas Frontera et al. (11) found equal enlargement of type I and II fibers.

There was a high degree of specificity in the training response. Strength performance measured on the training device (weight lifting) increased far more than in the less familiar isometric and isokinetic tests. Indeed, isometric and isokinetic performance failed to increase sig-

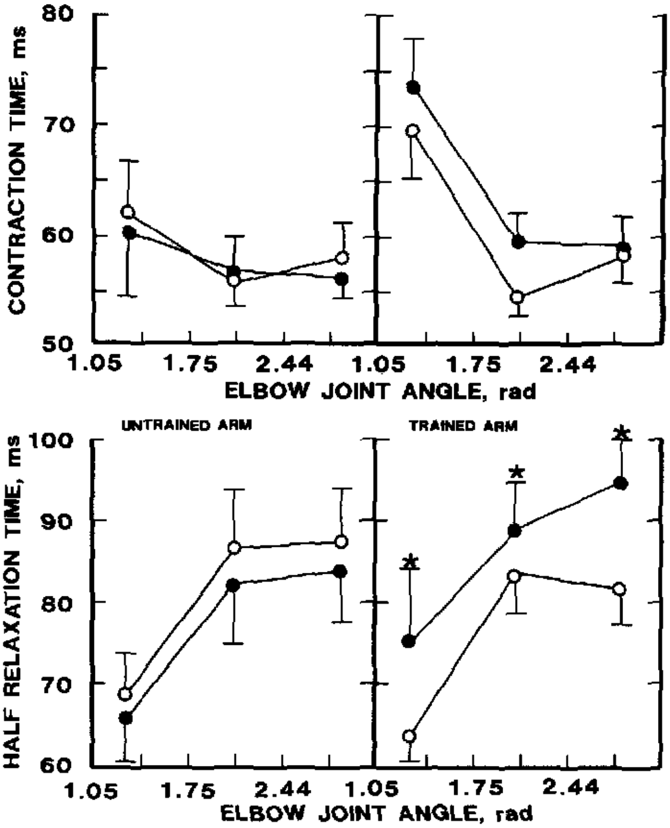

FIG. 6. Contraction times (*top*) and half-relaxation times (*bottom*) during electrically evoked twitch contractions of elbow flexors of both arms before (open circles) and after (filled circles) training. * $P < 0.05$, change after training.

nificantly despite a large (48%) increase in weight-lifting performance and a substantial amount of hypertrophy (17%). The observed specificity points to the important role of nervous system adaptations in the response to strength training, in particular the role of learning and coordination (30). The implication for the design of strength-training programs for the elderly is that the training exercises should simulate as closely as possible the most common strength-requiring tasks likely to be encountered by this population. Such an approach will ensure the best possible return on the training investment.

A puzzling finding was the lack of a significantly greater increase in isometric and isokinetic performance in the trained vs. untrained arm, because the trained arm underwent a greater increase in muscle and muscle fiber cross-sectional area. A greater increase in strength would be expected to accompany a greater increase in muscle mass. Such a finding is not unique to our study. In the study of Frontera et al. (11), the right knee extensors failed to increase isometric strength despite an 11.9% increase in muscle cross-sectional area. In the left knee extensors the increase in isometric strength (7.7%) was slightly less than the increase in muscle size (9.3%). Weight training in young men caused a greater increase in muscle cross-sectional area (10–17%) than isometric strength (4–5%); weight-lifting performance increased 24–42% (9). In a recent study in our laboratory (unpublished observations) we did not find a significant increase in isometric strength after 5 mo of weight training by young men despite significant increases in weight-lifting performance and muscle cross-sectional area. Finally, in a recent study no increase was found in the peak isometric force of overloaded rat soleus despite significant increases in muscle mass and muscle fiber area (16).

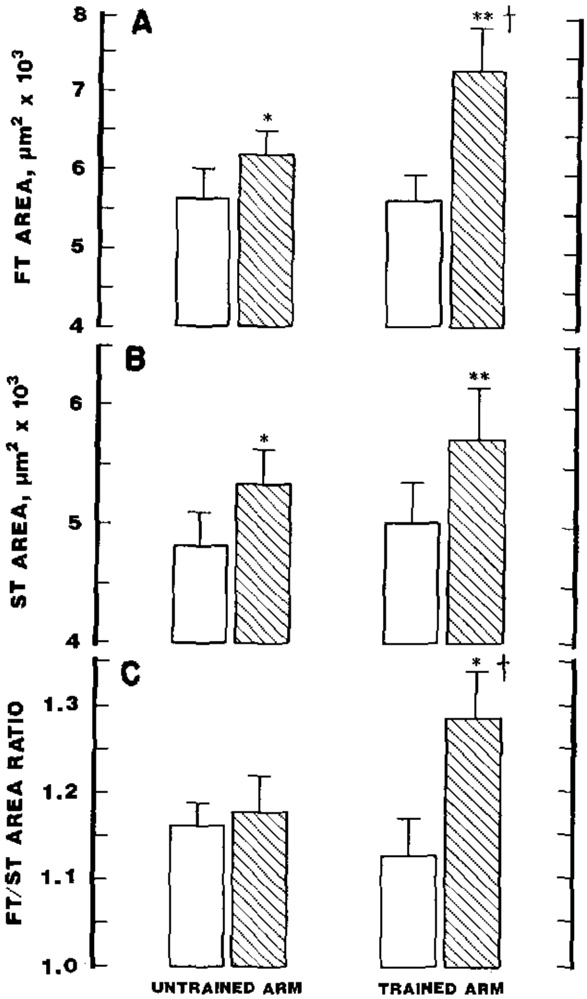

FIG. 7. Mean cross-sectional areas of type II (fast-twitch, FT; *A*) and I (slow-twitch, ST; *B*) fibers and FT-to-ST area ratios (*C*) in biceps brachii muscles of both arms before (open bars) and after (hatched bars) training. * $P < 0.05$, change after training (*A*–*C*); ** $P < 0.001$ and † $P < 0.001$, greater increase in FT vs. ST fibers in trained arm (*A*); ** $P < 0.01$, change after training (*B*); † $P < 0.05$, difference between arms (*C*).

It is difficult to explain why any measure of strength would not increase if muscle size increased. Perhaps in the present study training caused a "negative" neural adaptation, which took the form of inhibition of the elbow flexors during isometric contractions, thereby preventing increased force despite hypertrophy. This explanation can be excluded because motor unit activation in the flexors was near maximal and similar before and after training. A counterproductive neural adaptation might have taken the form of increased cocontraction of antagonists; thus increased cocontraction of triceps in the less familiar isometric task may have offset the increased contractile force of the agonists (elbow flexors). We have no data related to this possibility, although there is one report of greater cocontraction in the leg muscles of trained power athletes than endurance athletes (29). In view of the many complex ways in which the muscles acting at the elbow joint can be activated and coordinated (5), such seemingly counterproductive adaptations cannot be ruled out.

Perhaps the observed hypertrophy did not increase the intrinsic force-generating capacity of the muscle. It cannot be argued that hypertrophy in these older muscles was entirely the result of connective tissue proliferation, because the increase in fiber size was at least equivalent to that of the whole muscle. Furthermore the greatly hypertrophied muscles of bodybuilders show no evidence of connective tissue proliferation (32). In the previously cited study of rat soleus (16), hypertrophy after 30 days of overload was not associated with connective tissue proliferation, an increase in interstitial fluid volume, or a decrease in protein content. These authors suggested that ultrastructural examination of myofibrils and cytoarchitecture and assessment of possible alterations in excitation-contraction coupling might help uncover the mechanisms responsible for the decrease in specific tension (i.e., the force developed per unit muscle cross-sectional area) that can accompany hypertrophy. Whatever the mechanisms, they may account for the pattern of results found in the present study.

A notable observation was that muscle size increased significantly only in the right knee extensors and flexors even though both legs were trained simultaneously in a bilateral leg press movement. Perhaps most of the subjects were right limb dominant and unintentionally favored this limb during training.

In addition to the substantial gains in maximal weight-lifting capacity in this study, there was a notable improvement in muscular endurance during repeated lifting. After the training, subjects were able to lift their pretraining 1 RM from (range) 4 to 34 times in the trained limbs but only from 1 to 16 times in the untrained arm. By the seventh decade of life, losses in strength and power often interfere with many common activities of daily living, such as lifting and carrying, raising and lowering body weight, and walking. It seems likely that increases in muscular endurance of the type reported here might enable seniors to accomplish certain tasks that may otherwise prove to be impossible or extremely fatiguing.

Evoked twitch contractile properties. In the present study twitch torque increased in the trained arm at two of the three joint angles tested; however, a similar increase occurred at one of the joint angles in the untrained arm. Therefore there was no convincing evidence of a greater increase in twitch torque in the trained arm. These results are consistent with the lack of a greater voluntary isometric strength increase in the trained arm. Of the previously discussed mechanisms that might account for the failure of voluntary isometric strength to increase despite hypertrophy, only the possible decrease in specific tension can be offered to explain the failure of twitch torque to increase more in the more hypertrophied trained arm. Bodybuilders and weight lifters do have greater evoked twitch force than untrained men (33); however, these athletes had trained for many years and possessed greatly hypertrophied muscles. A greater degree of hypertrophy than we observed in the present study may be necessary before absolute muscle force begins to increase. Thus previous short-term longitudinal strength-training studies (1, 8, 26) in young subjects have mainly not shown increases in the evoked twitch and tetanic tension (Ref. 10 is an exception).

We elected not to use tetanic stimulation because of the extreme discomfort associated with the procedure. A limitation of using twitch torque as a measure of force-generating capacity is that the twitch response would be very sensitive to any alteration in excitation-contraction coupling; indeed, some investigators (10) use the twitch response as a measure of excitation-contraction coupling and the tetanic response as the measure of intrinsic force. It is possible that twitch and tetanic force could change independently. In a sense this happened in the present study. There was an increase in twitch but not tetanic (MVC with full activation) torque in both arms. If the increase in twitch torque was an adaptation to training, we cannot explain why the response was not greater in the more intensely trained arm.

Time to peak twitch torque did not change significantly in the trained arm, but there was a significant increase in half-relaxation time, in agreement with similar observations in young adults after strength training (18). The increase in half-relaxation time contributed to the increase in the twitch torque-time integral. The prolongation of the twitch contraction would shift the force-frequency relationship to the left, thereby allowing maximal tetanic tension to be achieved at a lower motor unit firing frequency. This adaptation coupled with the already observed slowing of older muscles even without training (35) should allow strength-trained seniors to achieve maximal muscle force at lower motor unit firing rates than their younger counterparts. Lower firing rates might also increase resistance to fatigue.

There was an apparent joint angle specificity in the changes in some of the twitch properties. At the smallest joint angle where the elbow flexors were at their shortest length, there were no changes in twitch torque, torque-time integral, or maximum rate of torque development. In contrast, at the largest joint angle and longest muscle length, these measures increased significantly but similarly in both untrained (actually received a mild training stimulus) and trained arms. The lack of change at the short muscle length may have resulted from the large in-series compliance at this length, which prevented all but a small part of the developed tension from being registered externally. The potential torque would already have been small because of the short muscle length. We are not able to explain why the untrained arm showed a decrease in twitch torque at the intermediate joint angle and muscle length after training while the trained arm showed an increase. Although the changes in MVC were not significant, the pattern of results was similar to that for twitch torque, namely, at the intermediate joint angle a decrease in the untrained arm but an increase in the trained arm. This pattern of results may have been influenced by the resistance pattern of the arm-training device because only the trained arm used it.

Motor unit activation. The elderly men in this study were able to fully activate their elbow flexors in maximal isometric contractions even before the training began. This observation confirms a previous report that the elderly are not impaired in the ability to activate muscles in voluntary isometric contractions (35). Both studies used the interpolated twitch method of assessing motor unit activation (4).

The method assumes that if no increment in torque occurs on a voluntary contraction recording when a supramaximal stimulus is superimposed, then the involved muscles have been fully activated. One possible criticism of the method might be that if the stimulus failed to fully activate the muscle and if the part not activated by stimulation was the same part not activated by voluntary effort, then it would be falsely concluded that voluntary activation was complete. However, such a happening is quite unlikely. Moreover, whereas the method is most sensitive when all motor axons have been stimulated, failure to do so does not invalidate the method (27, 31). The procedure that we and others have used to ensure the greatest possible activation by stimulation has been to use a stimulus intensity well in excess of that needed to evoke a maximal twitch response, the assumption being that no further increases in torque despite increases in stimulus intensity provide evidence that all motor fibers have been stimulated. Another indication that our stimulation maximally activated the elbow flexors was that the evoked twitch torque at rest (~8 N·m) was what you would expect for a tetanic (or MVC with full activation) torque of ~60 N·m, i.e., a twitch-to-tetanus ratio of ~0.15 for the elbow flexors (12, 26).

It must be emphasized that we determined motor unit activation only for isometric contractions, the contraction mode in which no improvement occurred after training. It is possible that before training the subjects were not able to fully activate their muscles in the weightlifting and isokinetic tasks in which performance improved.

In summary, we have demonstrated that older males can respond to progressive weight-lifting training with increases in dynamic muscle performance and whole muscle and muscle fiber size that compare favorably with responses seen in young men. These observations raise the encouraging prospect that the rate of decline in strength and muscle mass in old age and the accompanying loss of independent functional capacity can be reduced or even reversed by appropriate resistance training programs.

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APPENDIX B

B) i)
The number of repetitions that could be completed by the subjects after the training with a load that corresponded to their pre-training 1 RM.

EXERCISE	NUMBER OF REPETITIONS (RANGE)	(MEAN)
BENCH PRESS	5-10	7.0
LEG PRESS	10-34	19.0
ARM CURL (TRAINED)	4-22	14.0
ARM CURL (UNTRAINED)	1-16	7.0

APPENDIX C

(C) i) The maximum weight lifting strength of various muscle groups measured before and after 12 weeks of training.

MEASURE		PRE	POST
BENCH PRESS 1RM (kg)	MEAN	58.6	74.6*
	SD	9.5	11.4
LEG PRESS 1RM (kg)		155.7	191.7*
		11.4	13.5
ARM CURL 1RM (kg)		11.2	16.7*+
(TRAINED ARM)		1.7	3.2
ARM CURL 1RM (kg)		11.9	13.4*
(UNTRAINED ARM)		2.3	2.6

(* - P<.001)
(+ - denotes a significant difference (P<.001) between the trained and untrained arms post training.)

(c) ii) The maximal isokinetic torque of the legs (upper panel) and the arms (lower panel) before and after training.

BILATERAL LEG PRESS (N.m)

VELOCITY (°/S)		PRE	POST
15	MEAN	201.3	237.0
	SD	53.0	41.5
75		135.4	158.4
		32.2	22.9
			*

ARM FLEXION (N.m)

		TRAINED ARM		UNTRAINED ARM	
		PRE	POST	PRE	POST
30	MEAN	41.1	44.9	41.4	43.4
	SD	7.7	8.5	6.5	8.5
120		37.3	40.3	36.2	39.7
		6.2	8.5	6.5	8.5
180		33.1	37.4	31.6	34.7
		5.0	8.8	5.5	7.1
240		29.9	31.9	30.1	32.3
		4.2	3.7	6.7	8.9
300		27.7	29.7	30.1	30.4
		4.8	4.8	6.4	4.9
			**		**

(* - P<.001)
(** - P<.01)

(c) iii) The evoked contractile properties of the elbow flexors of both arms recorded at joint angles of 75, 120 and 165 degrees, before and after training.

JOINT ANGLE (DEGREES)		TRAINED ARM		UNTRAINED ARM	
		PRE	POST	PRE	POST
		PEAK TORQUE (N.m)			
75	MEAN	4.2	4.1	3.8	3.5
	SD	1.0	1.3	1.5	1.7
120		7.5	8.2*	7.7	6.8*
		1.4	2.3	1.6	1.9
165		7.5	8.4*	7.3	8.2*
		1.2	1.9	2.0	2.3
		MAX. RATE OF TORQUE DEVELOPMENT (N.m/s)			
75		129.8	120.5	122.9	131.2
		44.4	41.8	50.3	57.1
120		213.5	218.65	229.6	204.8*
		41.3	48.3	42.6	60.3
165		211.9	237.8*	202.7	232.5*
		32.4	63.4	44.5	63.7
		HALF RELAXATION TIME (ms)			
75		64.2	75.8	69.0	66.3
		14.1	29.4	18.0	20.4
120		84.0	89.5	86.8	82.7
		17.4	18.5	24.6	25.4
165		81.8	95.2	87.8	84.3
		12.6	17.1	22.6	21.5

*

* P < 0.01, difference between arms, upper two panels *

P < 0.05, change after training, bottom panel

(C) iv)
The maximum isometric strength of the elbow flexors before and after 12 weeks of training.

	JOINT ANGLE (degrees)			
MVC TRAINED ARM - (N.m)	75	MEAN	57.0	54.9
		SD	8.3	12.0
	120		57.7	59.7
			10.4	10.4
	165		37.6	41.1
			7.5	10.0
MVC UNTRAINED ARM - (N.m)	75		55.5	51.3
			7.6	11.1
	120		59.9	55.8
			9.6	10.2
	165		39.3	40.2
			9.6	10.5

(c) v)

MEAN CROSS-SECTIONAL AREA OF THE FLEXOR AND EXTENSOR COMPARTMENTS OF THE ARMS BEFORE AND AFTER TRAINING

TRAINED ARM

	PRE	POST	DIFF	%DIFF	P
FLEXOR AREA	16.73	19.61	2.88	17.21	<.001
(cm^2)	2.02	2.31			
EXTENSOR AREA	21.82	22.43	.61	2.8	-
(cm^2)	3.68	3.16			
BONE AREA	4.92	5.02	.1	2.03	-
(cm^2)	.52	.41			

UNTRAINED ARM

FLEXOR AREA	17.41	17.91	.5	2.9	-
(cm^2)	2.53	3.51			
EXTENSOR AREA	22.11	23.74	1.63	7.37	.035
(cm^2)	2.54	3.63			
BONE AREA	4.98	5.22	.24	4.82	-
(cm^2)	.4	.37			

(c) vi)

MEAN CROSS-SECTIONAL AREA OF THE FLEXOR AND EXTENSOR COMPARTMENTS OF THE LEGS BEFORE AND AFTER TRAINING

(This chart displays % as the mean of the sum of the individual%)

	RIGHT LEG			LEFT LEG		
	PRE	POST	%DIFF	PRE	POST	%DIFF
FLEXOR	77.55	81.17	4.4	76.13	74.91	-1.76
	10.67	14.24	14.24	11.04	13.46	5.75
EXTENSOR	68.84	75.74	9.87	66.63	67.44	1.48
	7.34	10.34	6.33	5.90	6.78	8.79
BONE	8.82	9.63	9.41	8.55	8.55	1.06
	.96	.99	8.71	.82	.72	8.43

(c) vii)

MEAN CROSS-SECTIONAL AREA OF THE FLEXOR AND EXTENSOR COMPARTMENTS OF THE LEGS BEFORE AND AFTER TRAINING

(This chart displays % difference as calculated from the mean of the pre and post scores.)

	RIGHT LEG			LEFT LEG		
	PRE	POST	%DIFF	PRE	POST	%DIFF
FLEXOR	77.55 10.67	81.17 14.24	4.67	76.13 11.04	74.91 13.46	-1.6
EXTENSOR	68.84 7.34	75.74 10.34	10.02	66.63 5.90	67.44 6.78	1.22
BONE	8.82 .96	9.63 .99	9.18	8.55 .82	8.55 .72	0

(c) viii)

MEAN CROSS-SECTIONAL AREAS OF TYPE I AND TYPE II FIBRES IN TRAINED AND UNTRAINED ARMS BEFORE AND AFTER TRAINING

	PRE	POST	Diff	% Diff	P
		TRAINED ARM			
TYPE I	5034.13	5724.02	689.89	13.7	.005
FIBRE AREA	1190.64	1574.05			
TYPE II	5616.92	7310.91	1693.99	30.16	.005
FIBRE AREA	1153.61	1972.14			
		UNTRAINED ARM			
TYPE I	4820.24	5345.4	525.16	10.89	.005
FIBRE AREA	1082.21	1002.14			
TYPE II	5608.62	6209.16	600.54	10.71	.005
FIBRE AREA	1404.7	1031.17			

(c) ix)

THE MEAN # OF TYPE I AND TYPE II FIBRES DIGITIZED IN BOTH TRAINED AND UNTRAINED ARMS BEFORE AND AFTER TRAINING

	TYPE I		TYPE II	
	PRE	POST	PRE	POST
UNTRAINED	99	82 29	100	90.2 14
TRAINED	100	76 23.5	100	86 22

(c) x) UPPER PANEL- The maximum cross-sectional areas of the elbow flexors and extensors determined by computed tomography in the trained and control arm, before and after training.
LOWER PANEL- The mean fibre area of the Type 1 and Type 11 muscle fibres in the elbow flexors of both arms, before and after the training period.

		FLEXOR AREA		EXTENSOR AREA	
		PRE	POST	PRE	POST
TRAINED	MEAN	16.7	19.6*	21.8	22.4
ARM (cm^2)	SD	2.0	2.3	3.7	3.2
UNTRAINED		17.4	17.9	22.1	23.7**
ARM (cm^2)		2.5	3.5	2.5	3.6

	TYPE 1		TYPE 2	
	PRE	POST	PRE	POST
TRAINED	5034.1	5724.0***	5616.9	7310.9***
ARM (μ^2)	1190.6	1574.1	1153.6	1972.1
UNTRAINED	4820.2	5345.4***	5608.6	6209.2***
ARM (μ^2)	1082.2	1002.1	1404.7	1031.2

(* - $P<.001$)
(** - P .035)
(*** - $P<.05$)
(+ - denotes a significant difference ($P<.05$) between the type 2 fibre areas of the trained and untrained arms post training.)

(c) xi)

% TYPE I FIBRES

	UNTRAINED ARM		TRAINED ARM	
	PRE	POST	PRE	POST
$\overline{X}$	45.07	45.14	39.36	39.71
SD	6.59	9.62	8.89	6.73

(c) xii)

FT/ST AREA RATIO OF THE TRAINED AND UNTRAINED ARMS BEFORE AND AFTER TRAINING

	UNTRAINED n=14			TRAINED n=14		
	PRE	POST	%	PRE	POST	%
$\overline{Y}$	1.16	1.18	1.7	1.13	1.29	14.2
SD	.13	.13		.17	.19	
SE	.03	.04		.04	.05	

APPENDIX D

PEAK TORQUE (N.m)

Untrained Arm

	75		120		165	
Subject	Pre	Post	Pre	Post	Pre	Post
AB	8.54	8.85	8.91	11.7	9.74	-
HB	4.31	3.74	10.65	9.98	9.22	10.59
JB	2.61	2.68	7.02	4.86	7.33	7.46
CB	3.82	2.24	6.99	6.01	5.37	7.87
HC	7.51	7.48	9.06	9.47	11.27	13.52
JC	3.8	1.1	8.16	7.2	7.69	8.38
AF	2.36	2.77	8.35	7.22	7.03	7.28
FF	3.16	2.13	5.03	4.04	4.43	4.43
HH	2.3	2.5	5.03	5.29	5.42	7.01
LH	5.83	2.85	11.55	8.53	-	-
JK	5.28	4.04	7.33	6.27	5.33	5.8
RP	3.39	3.44	8.99	5.34	9.97	7.78
FR	2.55	5.24	8	7.88	6.63	9.17
MS	4.39	4.24	7.73	8.51	7.56	8.59
X	3.79	3.47	7.7	6.84	7.29	8.16
S.D.	1.49	1.68	1.6	1.87	2.04	2.3

PEAK TORQUE (N.m.)

Trained Arm

	75		120		165	
Subject	Pre	Post	Pre	Post	Pre	Post
AB	6.7	9.04	8.09	11.11	9.27	9.48
HB	5.61	4.72	8.36	12.19	8.4	9.67
JB	3.35	4.53	6.36	7.53	7.29	7.81
CB	4.26	5.8	10.81	12.18	9.05	12.31
HC	5.73	3.96	7.54	8.09	9.7	9.6
JC	4.56	2.94	7.42	6.65	6.61	6.86
AF	5.27	4.46	7.68	8.43	8.13	8.79
FF	2.91	2.09	5.55	4.8	5.86	5.19
HH	2.69	3.14	5.75	6.39	6.84	7.34
LH	4.26	2.61	8.96	8.51	7.44	9.56
JK	4.36	6.4	7.97	7.33	6.63	6.59
RP	3.48	2.65	7.56	6.13	8.37	9.7
FR	4.32	4.95	6.76	10.25	6.85	9.67
MS	3.77	3.9	7.86	7.84	6.63	7.32
X	4.19	4.13	7.47	8.15	7.53	8.4
S.D.	1	1.28	1.37	2.31	1.17	1.92

MAX RATE OF TORQUE DEVELOPMENT (N.m./s)

Untrained Arm

	75		120		165	
Subject	Pre	Post	Pre	Post	Pre	Post
AB	248.6	221	276.2	303.8	276.2	
HB	119.7	138.1	313	267	221	-
JB	73.7	119.7	211.7	165.7	211.7	257.8
CB	156.5	128.9	239.4	184.1	147.3	193.3
HC	257.8	230.2	211.7	276.2	267	221
JC	101.3	46	248.6	211.7	239.4	386.7
AF	82.9	92.1	221	211.7	184.1	239.4
FF	111.2	64.4	176	128.9	148.2	221
HH	92.1	147.3	156.5	165.7	147.3	147.3
LH	193.3	101.3	432.7	267	-	174.9
JK	148.2	119.7	240.9	156.5	222.4	-
RP	138.1	138.1	267	147.3	276.2	165.7
FR	82.9	239.4	267	331.4	184.1	285.4
MS	110.5	110.5	202.5	211.7	184.1	248.6
X	122.91	131.2	229.61	204.83	202.73	232.48
S.D.	50.03	57.06	42.64	60.32	49.55	63.69

MAX RATE OF TORQUE DEVELOPMENT (N.m /s)

Trained Arm

	75		120		165	
Subject	Pre	Post	Pre	Post	Pre	Post
AB	184.1	202.5	230.2	276.2	257.8	257.8
HB	221	119.7	276.2	239.4	221	211.7
JB	92.1	119.7	174.9	230.2	230.2	202.5
CB	110.5	138.1	285.4	313	239.4	359.1
HC	202.5	156.5	211.7	230.2	267	322.2
JC	119.7	82.9	211.7	184.1	184.1	202.5
AF	138.1	119.7	257.8	257.8	211.7	248.6
FF	111.2	55.2	203.8	147.3	148.2	128.4
HH	82.9	92.1	165.7	193.3	211.7	202.5
LH	184.1	82.9	313	276.2	248.6	239.4
JK	92.7	193.3	194.6	202.5	203.8	221
RP	165.7	101.3	230.2	165.7	248.6	276.2
FR	119.7	184.1	165.7	276.2	184.1	285.4
MS	101.3	82.9	184.1	184.1	193.3	193.3
X	129.78	120.46	213.48	218.65	211.93	237.83
S.D.	44.41	41.8	41.26	48.27	32.43	63.41

HALF RELAXATION TIME (ms)

Untrained Arm

	75		120		165	
Subject	Pre	Post	Pre	Post	Pre	Post
AB	66	64	80	100	102	-
HB	52	48	92	66	90	86
JB	78	26	72	90	64	68
CB	94	58	76	64	94	90
HC	44	88	50	48	38	40
JC	60	42	112	124	100	112
AF	82	70	120	52	74	56
FF	100	82	102	106	112	100
HH	80	96	44	62	82	70
LH	40	86	34	96	-	-
JK	72	82	100	106	120	102
RP	56	66	70	114	76	92
FR	60	62	92	84	104	94
MS	50	76	112	76	100	102
X	69	66.33	86.83	82.67	87.83	84.33
S.D.	18.02	20.43	24.56	25.36	22.63	21.45

HALF RELAXATION TIME (ms) Trained Arm						
	75		120		165	
Subject	Pre	Post	Pre	Post	Pre	Post
AB	76	56	104	104	108	112
HB	60	64	114	84	88	96
JB	42	162	78	86	70	104
CB	84	62	90	66	74	60
HC	50	84	54	58	68	72
JC	76	64	66	116	96	120
AF	62	58	70	72	86	92
FF	76	80	78	118	70	94
HH	48	62	90	94	68	82
LH	66	118	62	98	90	98
JK	70	68	76	104	78	104
RP	50	46	94	100	82	106
FR	78	80	110	90	102	98
MS	74	80	88	86	100	95.17
X	64.17	75.83	84	18.49	81.83	17.09
S.D.	14.05	29.35	17.37		12.55	

TIME TO PEAK TORQUE (ms)

Untrained Arm

	75		120		165	
Subject	Pre	Post	Pre	Post	Pre	Post
AB	64	66	52	72	64	-
HB	84	66	56	76	68	68
JB	54	32	62	54	56	58
CB	62	104	60	58	74	48
HC	52	52	60	46	62	58
JC	86	80	44	50	48	58
AF	46	64	52	56	58	52
FF	40	54	46	48	52	54
HH	38	26	50	60	58	54
LH	56	64	48	50	-	-
JK	76	60	64	56	36	50
RP	64	52	56	52	58	64
FR	74	60	56	48	60	52
MS	68	74	64	78	70	58
X	62	60.33	55.83	56.83	58.33	56.17
S.D.	16.29	20.64	6.69	10.36	10.19	5.75

IMPULSE TO ½ RELAXATION TIME

Untrained Arm

	75			120			165	
Subject	Pre	Post		Pre	Post		Pre	Post
MS	.364	.411		.98	.854		.902	.885
FR	.26	.468		.799	.716		.755	.884
RP	.301	.301		.723	.632		.808	.789
JK	.552	.395		.863	.72		.593	.543
HH	.203	.203		.323	.452		.478	.584
FF	.316	.194		.521	.425		.52	.485
AF	.225	.275		.942	.535		.618	.532
JC	.4	.107		.836	.792		.756	.874
HC	.487	.665		.639	.615		.709	.798
CB	.439	.298		.667	.520		.617	.74
JB	.249	.1		.66	.465		.569	.572
BB	.414	.292		1.084	.933		.902	1.005
AB	.813	.787		.816	1.37		1.14	1.199

IMPULSE TO ½ RELAXATION TIME

Trained Arm

	75			120			165	
Subject	Pre	Post		Pre	Post		Pre	Post
MS	.345	.494		.841	.857		.686	.861
FR	.455	.494		.799	1.03		.836	1.062
RP	.308	.26		.705	.706		.712	1.047
JK	.389	.67		.659	.891		.507	.74
HH	.257	.278		.59	.615		.598	.708
FF	.309	.274		.513	.599		.494	.532
AF	.379	.348		.546	.673		.783	.865
JC	.482	.322		.609	.75		.664	.813
HC	.427	.387		.565	.546		.735	.75
CB	.546	.456		1.13	1.024		.885	1.001
JB	.329	.777		.603	.741		.576	.88
BB	.623	.418		1.009	1.325		.801	1.082

MVC (N.m)

Trained Arm

	75		120		165	
Subject	Pre	Post	Pre	Post	Pre	Post
AB	42.49	38.83	52.76	52.37	28.6	38
HB	61.44	58.82	57.82	70.75	34.29	36.03
JB	56.77	49.25	53.79	57.79	34.02	35.87
CB	72.08	73.32	77.06	71.61	42.5	63.86
HC	49.86	50.12	50.05	51.2	33.24	37.98
JC	50.09	29.47	52.5	55.38	33.02	37.39
AF	56.2	62.96	68.03	70.62	46.96	53.02
FF	50.83	43.07	46.15	48.25	28.32	29.75
HH	68.8	72.16	71.22	72.35	54.24	47.45
LH	64.01	58.07	70.46	66.38	36.46	38.05
JK	59.96	55.12	49.44	51.96	34.35	34.59
RP	47.91	49.61	47.11	43.25	35.48	32.42
FR	46.55	59.27	52.44	54.89	31.52	36.3
MS	63.32	55.29	67.25	68.45	43.42	47.89
X	56.98	54.87	57.74	59.71	37.61	41.05
S.D.	8.34	12.08	10.44	10.44	7.53	9.97

MAXIMUM RATE OF TORQUE RELAX (N.m/s)

Trained Arm

	75		120		165	
Subject	Pre	Post	Pre	Post	Pre	Post
AB	-92.1	-110.5	-82.9	-119.7	-82.9	-101.3
HB	-93.7	-64.4	-69.4	-101.3	-92.1	-110.5
JB	-55.2	-46	-64.4	-82.9	-128.9	-73.7
CB	-55.2	-76.7	-110.5	-147.3	-92.1	-165.7
HC	-82.9	-55.2	-110.5	-119.7	-147.3	-110.5
JC	-55.2	-36.8	-82.9	-55.2	-64.4	-46
AF	-92.1	-55.2	-101.3	-92.1	-92.1	-73.7
FF	-37.1	-27.6	-64.9	-36.8	-55.6	-46
HH	-55.2	-55.2	-64.4	-64.4	-82.9	-73.7
LH	-55.2	-27.6	-92.1	-73.7	-64.4	-101.3
JK	-55.6	-73.7	-92.7	-73.7	-101.9	-73.7
RP	-55.2	-46	-82.9	-55.2	-110.5	-73.7
FR	-36.8	-46	-55.2	-92.1	-55.2	-82.9
MS	-46	-55.2	-73.7	-73.7	-55.2	-64.4
X	-58.35	-52.92	-80.65	-82.87	-89.85	-82.88
S.D.	16.8	13.69	19.31	30.42	29.67	32.85

MAXIMUM RATE OF TORQUE RELAX (N.m/s)

Untrained Arm

	75		120		165	
Subject	Pre	Post	Pre	Post	Pre	Post
AB	-128.9	-101.3	-138.1	-110.5	-119.7	-
HB	-64.4	-55.2	-101.3	-119.7	-128.9	-138.1
JB	-36.8	-82.9	-73.7	-46	-92.1	-92.1
CB	-55.2	-27.6	-82.9	-64.4	-55.3	-110.5
HC	-119.7	-110.5	-128.9	-174.9	-184.1	-230.2
JC	-55.2	-27.6	-110.5	-110.5	-92.1	-101.3
AF	-55.2	-36.8	-101.3	-92.1	-33.7	-101.3
FF	-37.1	-27.6	-46.3	-36.8	-37.1	-46
HH	-46	-64.4	-73.7	-69.4	-55.3	-92.1
LH	-119.7	-46	-221	-110.5	-	-
JK	-55.6	-36.8	-64.9	-64.4	-55.6	-46
RP	-55.2	-55.2	-119.	-36.8	-65.7	-64.4
FR	-36.8	-64.4	-73.7	-82.9	-55.2	-82.9
MS	-64.4	-46	-64.4	-110.5	-55.2	-92.1
X	-56.8	-52.92	-86.77	-83.62	-87.52	-99.75
S.D.	22.13	25.19	-25.21	40.52	47.78	48.71

TIME TO PEAK TORQUE (ms)

Trained Arm

	75		120		165	
	Pre	Post	Pre	Post	Pre	Post
AB	68	78	60	68	58	60
HB	86	74	50	78	56	74
JB	88	86	58	64	58	70
CB	86	56	62	58	74	62
HC	56	54	60	46	56	52
JC	70	86	56	56	54	54
AF	50	60	46	52	58	52
FF	74	92	52	56	60	58
HH	84	62	52	50	66	60
LH	50	64	56	54	56	60
JK	64	82	50	64	42	48
RP	56	92	46	62	48	56
FR	68	58	56	56	68	54
MS	52	82	66	72	60	72
X	69.5	73.67	54.5	59.5	58.38	59.33
S.D.	14.15	14.72	6.27	9.11	8.56	8.54

TIME TO PEAK TORQUE (ms)

Untrained Arm

	75		120		165	
Subject	Pre	Post	Pre	Post	Pre	Post
AB	64	66	52	72	64	-
HB	84	66	56	76	68	68
JB	54	32	62	54	56	58
CB	62	104	60	58	74	48
HC	52	52	60	46	62	58
JC	86	80	44	50	48	58
AF	46	64	52	56	58	52
FF	40	54	46	48	52	54
HH	38	26	50	60	58	54
LH	56	64	48	50	-	-
JK	76	60	64	56	36	50
RP	64	52	56	52	58	64
FR	74	60	56	48	60	52
MS	68	74	64	78	70	58
X	62	60.33	55.83	56.83	58.33	56.17
S.D.	16.29	20.64	6.69	10.36	10.19	5.75

MVC (N.m)

Untrained Arm

	75		120		165	
Subject	Pre	Post	Pre	Post	Pre	Post
AB	54.55	40.48	55.38	54	33.72	-
HB	61.36	67.37	65.72	65.64	38.82	40.56
JB	55.31	46.55	55.33	56.17	35.28	32.48
CB	67.35	55.24	75.14	66.29	38.34	51.75
HC	51.08	42.3	66.27	51.73	40.06	39.24
JC	55.63	41.27	54.8	56.15	36.68	36.17
AF	63.93	60.2	64.61	64.55	35.5	42.33
FF	46.94	38.65	45.5	38.88	28.7	24.76
HH	66.22	52.74	68.29	59.98	55.48	48.8
LH	75	60.79	77.48	70.1	-	-
JK	47.74	40.14	47.95	41.78	25.37	23.88
RP	54.58	47.45	65.22	52.2	47.88	36.69
FR	46.23	49.65	46.55	45.88	32.96	45.85
MS	49.25	73.68	63.63	70.65	56.46	59.6
X	55.47	51.27	59.92	55.82	39.29	40.18
S.D.	7.63	11.13	9.61	10.16	9.61	10.51

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