THE EFFECT OF RESISTANCE TRAINING
ON STRENGTH DEVELOPMENT
IN PREPUBESCENT BOYS

BY

JEAN RAMSAY, B.Sc.

A thesis

Submitted to the School of Graduate Studies

in Partial Fulfilment of the Requirements

for the Degree

Master of Science

McMaster University

RESISTANCE TRAINING IN

PREPUBESCENT BOYS

MASTER OF SCIENCE
McMaster University
(Adapted Human Biodynamics)
Hamilton, Ontario

TITLE: The effect of resistance training on strength development in prepubescent boys.

AUTHOR: Jean Andre Ramsay, B. Sc. (McGill)
B. Sc. (University of Ottawa)

SUPERVISOR: Cameron J.R. Blimkie, Ph.D.

NUMBER OF PAGES: xiii, 248

ABSTRACT

The present investigation was undertaken to examine the effects of resistance training on maximal voluntary strength, muscle cross-sectional area and contractile properties in prepubescent boys. A second purpose was to observe the time course and identify the possible mechanism(s) underlying strength development in this population.

Thirteen boys (9-11 y) volunteered for each of the training (T) and control (C) groups. Training consisted of between 3-5 sets of six exercises. Subjects trained 3 times weekly for two phases of 10 weeks at intensities between 75-85 % of the 1 repetition maximum (RM). Performance measures (1RM) were recorded for bench press (BP) and leg press (LP) on a Global Gym Station for both experimental and control groups. The 1 RM double arm curl and leg extension were measured for the experimental group only, on the training device. Maximal voluntary isometric strength (MVC), isokinetic strength (IS) and contractile properties were measured for the right elbow flexors (EF) and knee extensors (KE). The interpolated twitch technique was used to determine % motor unit activation (MUA) and computerized axial tomography (CAT) was used to determine EF and KE cross-sectional area (CSA). All data were analysed using

ANOVA with a Tukey post hoc test, with the exception of % MUA (Friedman two-way analysis of variance).

High day to day and trial to trial reliability was obtained for voluntary strength measurements. Wide fluctuations were observed in day to day and trial to trial reliability of the evoked contractile properties. While CAT was judged a satisfactory method for measuring total limb and total lean cross-sectional area, questions were raised concerning the reliability and accuracy of the technique in discerning between individual muscle bellies.

Significant training effects on voluntary strength were observed for BP (+35 %), LP (+22 %), EFIS (+26 %), KEIS (+ 20 %), EFMVC (+37 %) ($P<.01$), and at joint angles 90° and 120° for KEMVC ($P<.05$). Muscular endurance, defined as the number of repetitions performed at the end of the study with the pre-test 1 RM, was also significantly increased for the BP and LP with training ($P<.01$). For the contractile properties, training significantly increased EF (+30 %, $P<.01$) and KE (+30 %, $P<.05$) twitch torque. With the exception of EF maximum rate of torque relaxation (MRTR) (+20 %, $P<.05$) all other time-related contractile properties were not affected by training. However, maximum rate of torque development (MRTD) for both muscle groups showed a trend toward increasing. There were no significant effects of training on CSA or % MUA, however, there was a trend towards increased MUA for elbow flexion and knee extension in the trained group.

In conclusion, resistance training increased voluntary strength of EF during both phases of training. Voluntary strength of KE increased mostly during the first 10 weeks of training. Although the strength gains were independent of changes in muscle CSA, significant increases in twitch torque combined with trends in some of the time-related contractile properties, during the second phase of training, suggest possible adaptations in muscle extensibility or excitation-contraction coupling. While these changes may explain part of the observed increases in strength, neurological adaptations such as increased MUA, improved motor skill, better co-contraction of the synergist muscle groups and increased inhibition of the antagonist muscle groups are likely the major determinants of the strength gains in this study.

ACKNOWLEDGEMENTS

I wish to thank my advisor and friend, Dr. C.J. Blimkie for his constant encouragement, advice and enthusiasm during the course of this investigation. Thanks are also expressed to Dr. D.G. Sale, whose door was ever open to me and whose willingness to share his knowledge with me resulted in many enlightening discussions. Special thanks, also goes to Joan Martin, with whom I developed a genuine friendship, and who as coordinator of the study, oversaw numerous logistical aspects and helped in the collection of data. I also wish to thank Dr. D. Elliot and Dr. T. Lee for their advice on statistical procedures and J. Moroz for his patience and technical assistance. Finally, I must express gratitude to my future wife, Adele, for her patience and faith in me during this project. She has lived with the manuscript for a long time, and she is probably even more pleased than I am that it is finished.

TABLE OF CONTENTS

LIST OF TABLES

PAGE

LIST OF FIGURES

PAGE

Chapter I

Introduction

The adult population at large has borrowed eagerly from the training and conditioning program of athletes in order to improve general fitness. Jogging, aerobic dancing, bicycling and weight training are among the most popular activities used by adults on a regular basis to increase the fitness level.

Muscle strength represents a basic fitness component. Not only is it an essential aspect of sport conditioning, but it is an important and often neglected component of physical fitness, especially among youth. In the United States studies have shown a trend for reduced strength performance in children during the past decade.

With regard to children, a controversy surrounds the development of muscle strength with resistance training. Questions have been raised concerning the efficacy of resistance training in improving strength in children, especially before puberty. A second concern is the risk of both acute and chronic injuries associated with weight training, regardless of the possible benefits in strength gains and improvement in fitness. In addition, it has been suggested that weight training may provide a protection against possible injuries incurred during other sport activities, during childhood.

While each of these questions is important in its own right, this thesis will focus primarily on the efficacy of resistance training in prepubertal children. This is an especially pertinent question since there is some doubt that prepubescent children are capable of making significant gains in strength since they lack adequate levels of androgens. Additionally, this thesis will investigate the possible mechanism(s) underlying strength development with growth and resistance training in prepubertal boys.

Several studies involving children (Servedio et al., 1985; Pfeiffer & Francis, 1986; Sewall & Micheli, 1986; Weltman et al., 1986; Funato et al., 1987; Sailors & Berg, 1987) have reported significant increases in strength following various modes of resistance training. However the results are equivocal; some studies have also reported insignificant gains in strength (Vrijens, 1978; Docherty et al., 1984; Funato et al., 1987) following strength training programs.

Numerous factors may contribute to the inconsistency of results in this area. A relatively short duration of training (<10 weeks) has proven to be a limiting factor in many of the reviewed studies (Vrijens, 1978; Docherty et al., 1984; Servedio et al., 1985; Sewall and Micheli, 1986; Sailors & Berg, 1987). Although short term studies may provide information about acute adaptations to training, they may prove to be a major limitation if one is interested in determining the mechanism(s) underlying more chronic adaptations to training. In adults, both neural and muscular adaptations are believed to be responsible for the increase in strength following chronic strength training (Moritani and DeVries, 1979). Attempts to establish the time course of these adaptations in adults has been studied only recently (Moritani & DeVries, 1979; Sale & MacDougall, 1981; Davies & Young, 1983; Hakkinen & Komi, 1983; Hakkinen et al., 1985; Hakkinen & Komi, 1986). There is no information on the nature and time-course of neuro-muscular adaptations in response to resistance training for children.

Since strength is positively correlated with body weight during childhood (Malina, 1975; Haines, 1985) the incorporation of an age- and size-matched control group is a major concern in strength training studies, to account for the effect of growth on the dependent variable. For example, Vrijens (1978) in an often quoted study in the literature, failed to use control groups, making it impossible to discriminate between the effect of weight training and the influence of growth on the strength development of prepubescent boys.

The magnitude of the training stimulus will also have a dramatic effect on strength adaptations. Strength gain in adults is known to be dependent upon factors such as duration, frequency and load (the product of intensity and volume) of training. Little is known concerning the effect of these factors on strength gain with resistance training before puberty. Presently, there is no scientific support for the acceptance of training programs based on training principles derived from adult studies for youth. Strength training programs for children tailored on adult studies may prove inadequate, by causing either overtraining or providing an insufficient stimulus for strength gains.

While muscular and neural adaptations to training will probably influence strength, other factors must be considered when assessing strength development. Structural and biomechanical factors are susceptible to change in growing children and may also affect strength. These have not been considered in previous studies in the context of resistance training programs involving children.

The exercise mode used for resistance training in these studies may partly account for some of the inconsistent results in the literature.

Studies have often incorporated one mode of exercise during training, and a different mode of exercise in the assessment of strength changes. Additionally, different exercise modes (eg. isometric versus hydraulic) have been used by various investigators (Vrijens, 1978; Servedio et al., 1985; Sewall & Micheli, 1986; Sailors & Berg, 1987) , making it difficult to compare results across studies. In order to avoid these problems, specific and non-specific testing modes have been used in the present investigation to assess strength.

Lastly, the strength training device used for training shouldrepresent what is likely to be available in the children's environment. Although isokinetic and variable resistance equipment such as Hydra-Gym and Nautilus offer safety advantages for the beginner, they represent a substantial financial investment for the individual or the school and often are not designed for use by children. Few studies (McGovern, 1984) have investigated the effects of a traditional weight training program, employing conventional training methods and equipment on strength development in children.

Summary

While recent studies suggest that prepubertal children may increase strength using special training equipment and procedures, there is a dearth of information concerning the effect of a traditional strength training program using isotonic contractions and conventional weight training equipment on the development of strength in prepubescent children. In addition, little is known about the mechanism(s) underlying strength adaptations or the time course of these adaptations in prepubertal boys, in relation to resistance training.

Purpose

The main purpose of this study is to examine the effects of 20 weeks of training, using a traditional, progressive resistance approach on maximal voluntary and evoked strength, muscle cross-sectional area and contractile properties of muscle in prepubertal boys. A secondary purpose is to determine the time course of, and to identify the mechanism(s) underlying strength development in this population. It is hoped that the procedures and methods used in this study will provide additional and unequivocal information regarding the efficacy of strength training for the prepubertal population.

Chapter II

Review of literature

A. Effect of resistance training on voluntary strength in prepubescents

1. General findings

Table 1 gives a brief description of studies that have examined the effect of resistance training on strength development of prepubescent children. Although all but one (Docherty et al., 1984) study have reported significant increases in strength with resistance training during prepuberty, the magnitude of the strength gain varies considerably from one study to the other.

For instance, Vrijens'study (1978) found an increase of 35 % for the back and abdominal muscles of prepubescent boys, following 8 weeks of weight training, while no training effect was observed in the strength of the extremities. In contrast, Weltman et al., (1986) observed significant increases in isokinetic torque, ranging from 13 to 45 % for muscle groups of the arm and leg in prepubertal boys.

The discrepancy in results between these two studies and others, invite an examination of the particular training program and subject populations chosen for these investigations. In adult studies, the magnitude of the

Table 1. Summary of resistance training studies in prepubescent children. List of abbreviations :

EE : elbow extension
EF : elbow flexion
Hydraulic. : hydraulic resistance
Isok. : isokinetic contraction
Isom. : isometric contraction
Isot. : isotonic contraction
KE : knee extension
KF : knee flexion
NS : non-significant
Pneumat. : pneumatic resistance
RM : repetition maximum
r/s : radians per second
S : significant
TE : thigh extension
TF : thigh flexion

Table 1. Summary of resistance training studies in prepubescent chil dren.

Reference	Subjects Sex	Grou.	Age (y)	Num (n)	Muscle train. or exerc.	Dura. (wks)	Freq. (d/wks)	Test. mode	Training mode	Load isot. (% 1 RM or n RM)	Load isom. (cont. time) (s)	Volume (sets x reps)	Increase in voluntary strength (%)	Increase muscle hyper-trophy (%)
Vrijens 1978	M	a) b)	16.7 10.4	16 12	KF, KE, EF, EE, Back, Abdom..	8	3	Isom.	Weight train.	75		1 x 8-12	a) 15-33 b) 35-36	a) 5-14 b) NS
Nielsen et al. 1980	F	a) b)	13.5 -19 <13.5	83	KE	5	3	Isom.	Isom.	-	?	1 x 24	a) 32 b) 40	-
Docherty et al. 1984 (abstract)	M	a) b) c)	11.6	30	KF, KE, TF, TE, Shou. press, Bench press, Arm adduc., Arm abduc.,	6	3	Isok.	Hydraul. a) 3.14r/s b) 0.53r/s c) mix ve.			2 x 20s	a) NS b) NS c) NS	-
McGovern 1984 (abstract)	M-F		-	42	Bench press, Pulley, Curl Chin-ups.	12	3	Isot.	Weight train.	?		?	S	NS
Servedio et al. 1985 (abstract)	M		11.9	12	Snatch, Clean and Jerk.	8	3	Isok.	Olymp. lift.	?		-	S	-
Pfeiffer and Francis 1986	M	a) b) c)	19 12 10	20 30	KE Bench press Curl.	9	3	Isok. 0.53 r/s 2.09r/s	Weight train.	38-56-75		3 x 10	a) 6 b) 12 c) 12 a) 5 b) 10 c) 25	-
Sewall and Micheli 1986	M F		10-11 10-11	7 3	Chest press, Back rowing, Leg press.	9	3	Isom.	Pneumat.	38-60-75		3 x 10	SF 95.8 KE-KF NS SE NS	-
Weltman et al. 1986	M		8.2	28	EF, EE, Shou. press, Bench press Hip adduc., Hip abduc., Flys Jump squat	14	3	Isok.	Hydraul.			3 x 30s	13-45	NS
Funato et al. 1988	M-F		6-11	99	EF	12	3	Isom. Isok. 1.05r/s 3.14r/s 5.24r/s	Isom.		10s	2 x 3	EF NS EE 17.5 NS NS NS	EE 10-25 EF 12-15
Siegel et al. 1988 (abstract)	M-F		8.5	90	Calisthenics Stretch tub., Handheld wts, Balls.	12	3	Isom. Isot.	Isot.	?		-	12 55	-

adaptive response to resistance training is dependent upon the frequency, duration, intensity, mode of training and testing, gender, age and training status of the subjects (Fleck & Kraemer, 1987) For children, all of the above factors are important, but the maturity level, because of its influence on growth and neuro-humeral function, must also be considered.

2. Design considerations

While the training frequency of studies highlighted in Table 1. was similar (3 days/week), wide fluctuations are observed regarding other program variables. Comparable results in strength gains have been observed using both short and long duration programs. Nielsen et al. (1980) reported a 40 % increase in isometric knee extension torque in girls 7-13.5 years of age, after only 5 weeks of isometric training. The investigation by Weltman et al. (1986), represents the longest resistance training study to date involving prepubescent children. Fourteen weeks of hydraulic resistance training produced significant increases in isokinetic strength ranging from 13 to 45 % for elbow flexion and knee extension and flexion at two velocities of contraction (0.52 and 1.57 $rad \cdot s^{-1}$). No significant training effect (interaction between time and training) was observed for elbow extension. However, subsequent t-test analysis revealed that the average change in torque score (mean of 9 torque measurements across the range of motion) of the experimental group was greater than that of the control group, indicating a similar trend for elbow extension as for the other three movements.

In comparison, however, a study published as an abstract (Docherty et al., 1984) using a similar mode of training, showed no improvement in isokinetic torque of knee extension and flexion or of elbow adduction and abduction. While Funato et al. (1988) showed an increase of 17.5 % in elbow extension after 12 weeks of isometric training, no significant increase was found for elbow flexion, in which the maximum training effect was expected. Other studies of intermediate duration have observed relatively high (Servedio et al., 1985) and low strength gains (Vrijens, 1978; Pfeiffer & Francis, 1986; Sewall & Micheli, 1986).

An important factor that may affect the strength increase is the mode of testing and training used. The "mode" refers to the type of muscular contraction utilized to execute the training exercises or to measure the strength performance. The advantage of using different modes for testing and training is that the strength gain is less likely to depend on learning and coordination of the muscles to execute the movement. This is an especially important factor for studies of a short duration, since the learning effect will manifest itself at the beginning of the training program (Sale, 1987). A disadvantage is that monitoring the strength improvements with a different mode, may mask some of the strength gains because of specificity of the contraction type (Rutherford & Jones, 1987; Sale, 1987).

This could partly explain the poor results obtained in some studies (Vrijens, 1978; Pfeiffer & Francis, 1986; Sewall & Micheli, 1986) where different testing and training exercise modes were used. This is further illustrated in a study by Siegel et al., 1988, in which two modes of testing were used to measure strength changes. Isometric strength as measured by cable tensiometry showed no increase, but isotonic strength of the elbow flexors measured by pull-ups increased by 55 %. Boys and girls were trained with calisthenics and exercise using stretch tubing, hand weights and balls. Isometric strength of the right-hand increased by only 12 % and no significant changes were observed for other isometric strength measurements including left-hand grip or elbow extension, measured by cable tensiometry.

3. Training intensity

The intensity of training represents the single most important variable in a resistance training program designed to increase muscle strength. It combines the load, which is defined as a % of the one repetition maximum

(1RM), and the volume of training, which represents the actual number of sets and repetitions performed by the subject, within a time period. In order to induce adaptations from resistance training, the specific muscle group in which these adaptations are sought must be subjected to a training overload. This overload is typically achieved by having the subject perform sets of progressively increasing resistance to failure.

The intensity of training will also be affected to a lesser degree by the sequence of the exercises and the method of training. Most studies dealing with children have used a circuit training approach rather than the straight set method, which is used more commonly by adults. The circuit method consists of performing one set of an exercise and then moving to the next exercise and so on, until a circuit is completed. This circuit is normally repeated one or two times. With the straight set method, the subject performs three sets or more of the same exercise before moving to the next exercise. The latter method is considered more intense because a greater load can be used since the subject is not doing any work during the rest period.

Because of the limited number of studies on prepubescent resistance training it has been difficult to establish precise guidelines regarding training intensity. So far researchers have established training intensity, based on conservative versions of adult studies because of an overwhelming concern for injury. This has resulted in programs of relatively low training intensity (Pfeiffer & Francis, 1986; Sewall & Micheli, 1986), which may not provide sufficient overload for optimal strength gain.

Two studies (Pfeiffer & Francis, 1986; Sewall & Micheli, 1986) used training of a comparable intensity; 3 sets of 10 repetitions at a load between 38 and 75 % of the 1 RM. Sewall & Micheli (1986) showed a pattern of increased isometric strength for all the muscle groups tested, but the increase was only significant for right shoulder flexion. Other measures of strength including left shoulder flexion, shoulder extension and knee extension and flexion were not significantly increased by training. The study of Pfeiffer & Francis (1986) showed significant increases in torque for the right elbow flexors and extensors and the right knee extensors at two velocities of contraction (0.52 and 1.09 $rad \cdot s^{-1}$). For the left limbs, only elbow flexor torque at 0.52 $rad \cdot s^{-1}$ and knee extensor torque at 2.09 $rad \cdot s^{-1}$ were increased.

The training intensity of these two studies was similar to that of Vrijens'study (1978) which only used one set at 75 % of the 1 RM and which also produced only limited strength gains. While Pfeiffer and Francis (1986) and Sewall and Micheli (1986) used three sets, the first two sets performed at sub-maximal load served as a warm-up, and only the third set was performed to failure.

In three studies published as abstracts (McGovern, 1984; Servedio et al., 1985; Siegel et al., 1988) no details were given regarding the specifics of the training intensity. Based on the results from these studies, it appears that resistive type activities like calisthenics (McGovern, 1984; Siegel et al., 1988) provided sufficient overloading of the musculature to elicit significant strength gains. Olympic style lifting (Snatch and Clean and Jerk) which typically involves loads between 80 and 100 % of the 1 RM and a high volume of training, also seems to have a favorable influence on strength development during chilhood (Servedio et al., 1985).

It is more difficult to quantify the intensity of training programs that use hydraulic resistance training (Docherty et al., 1984; Weltman et al., 1986). Since the resistance offered by the training device depends on the effort given by the subject, it is imperative that the subject be well motivated. In these studies, the volume of training was quantified in terms of the duration of each set, rather than by the absolute number of repetitions performed per set. In the study by Docherty et al. (1984) subjects did 2 sets of 20 seconds compared to 3 sets of 30 seconds in the study by Weltman et al. (1986). While no direct comparison can be made regarding the degree of motivation displayed by the subjects in these studies, a greater volume of training was done by the subjects in the Weltman et al. (1986) study. This higher training volume coupled with a longer duration of training may explain why Weltman et. al. (1986) observed an improvement in voluntary strength (torque) whereas Docherty et al. (1984) failed to show any effect of training on strength development in their study.

B. Effects of resistance training on strength performance- comparison between prepubescent and adult studies

It is of interest to determine if prepubescent children are capable of making gains in strength which are comparable to those found in older age groups. This question can be addressed by either comparing absolute or relative (%) changes in strength between groups. If the absolute increase in strength is used, it may tend to favor the older age groups. Being stronger initially, they may experienced a greater absolute increase in strength after training. While the percentage increase appears to be unbiased toward any group, it may favor the prepubescents. In this case, an increase in strength may translate into a higher percent increase for younger subjects because of a low initial level of strength. In order to make the comparison as equitable as possible, wherever possible, both absolute and percentage increases will be reported for prepubescent children and adult groups. A summary of the strength trainability of children, utilizing this approach has recently been provided by Sale (1989, in press).

In some of the studies (Vrijens, 1978; Nielsen et al., 1980; Pfeiffer & Francis, 1986) discussed in the previous section, groups of older subjects were incorporated with the prepubescent children, enabling direct age-group comparisons of strength results. Vrijens (1978) observed greater absolute and % changes in isometric strength of the extremities in postpubescents (4 to 9 kg or 17 to 33 %) compared to prepubescent (-1.0 to 0.6 kg or -4 to 6 %) boys. In contrast, increases in back and abdominal isometric muscle strength were more similar, 18 and 11 kg for the postpubescent compared to 17 and 6 kg for the prepubescent boys. In relative terms, the prepubescent boys displayed an increase in strength of 20 and 10 % higher than those found for their postpubescent counterpart, for back and abdominal muscles (20 and 10 % higher, respectively).

Nielsen et al., (1980) found that the % change in isometric strength of the knee extensors was slightly higher for girls below 13.5 years of age (40 %) than for girls between 13.5 and 19 years (32 %). Similarly, in a study by Pfeiffer and Francis (1986) prepubescent boys displayed an average change in isokinetic torque of 19 % compared to 11 % for pubescent and 6 % for postpubescent boys. In another study (Sailors & Berg, 1987), pubescent males demonstrated increases in weight lifting strength (5 RM) between 20 and 52 %, which was comparable to the increases made by a group of young adults (20 to 35 %). In absolute terms, the increases in strength for the adults (7 to 28 kg) were not much higher than the increases in strength achieved by the pubescent group (3 to 22 kg).

In general, results of studies (Table 2) (Gallagher et al., 1949; Delorme et al., 1952; Kusinitz & Keeney, 1958) that have examined the effect of weight training on pubescent- and post-pubescent groups have reported high percentage strength increases (42 to 197 %). Kusinitz and Keeney (1958) reported that strength increased in five different exercises, ranging from 60 % (11 kg) for the military press to 197 % (41 kg) in the squat. One explanation for the greater increases in strength in these studies than in those involving prepubescent children (Vrijens, 1978; Pfeiffer & Francis, 1986) is that weight lifting was used for both training and testing.

Table 3 gives a summary of selected resistance training studies in adults. MacDougall et al. (1977 and 1979) reported increases in isokinetic strength of 28 and 91 % in adult male subjects, following weight training. This increase is larger than the 6 % increase observed by Pfeiffer and Francis (1986) for prepubescent boys. The

Table 2. Summary of resistance training studies pubescent and postpubescent children. List of abbreviations :

BE : back extension
EF : elbow flexion
Hip-KE : Hip-knee extension
Isok. : isokinetic contraction
Isom. : isometric contraction
Isot. : isotonic contraction
KE : knee extension
KF : knee flexion
NS : non-significant
Plyom. : plyometric
RM : repetition maximum
S : significant
var. re. : variable resistance

Table 2. Summary of resistance training studies in pubescent and post-pubescent children.

Reference	Subjects Sex	Subjects Grou.	Subjects Age (y)	Num (n)	Muscle train. or exerc.	Dura. (wks)	Freq. (d/ wks)	Testing mode	Training mode	Load isot. (% 1 RM or n RM)	Load isom. (cont. time) (s)	Volume (sets x reps)	Increase in voluntary strength (%)	Increase muscle hyper-trophy (%)
Gallagher et al. 1949	M M M	a) b) c)	16.2 16.7 15	25 9 8	KE BE Chest-arm	a) 4-12 b) 2-12 c) 6-15	4 4 4	Weight lift.	Weight train.	? ? ?		2-3 x 10 2-3 x 10 2-3 x 10	a) 110* b) 169* c) 73-110	-
DeLorme et al. 1952	M	a) b) c)	?	10	a) EF b) KE c) Hip-KE	16	4	Weight lift.	Weight train.	?		?	a) 59 b) 49 c) 42	Arm 31
Kusinitz and Keeney 1958	M		12-17	46	Squat, Curl, Bench press, Shou. press, Pullover.	8	3	Weight lift.	Weight train.	8 RM		1-3 x 8-12	60-197	Thigh 4 Arm 7 Chest 7
Smith and Melton 1981	M	a) b) c)	16-18	12	KF, KE.	6	3	Isom. Isot. Isok.	a) var. re. b) low isok. c) high isok.	80		3 x 10 50% fat. 50% fat.	a) 13 b) 8 c) 8 a) 8 b) 18 c) 31 a) 11 b) 10 c) 7	-
Steben and Steben 1981	M F	a) b) c)	? ?	80 80	a) Depth jum. b) Box drills c) Hopping and bounding	7	5	high jump long jump tri. jump	Plyom.	height 254 cm height 254 cm		1 x 10-12 1 x 10-12 -	a) 6-9 b) 6-13 c) 5-13	-
DeKoning et al. 1984	M		16.1	29	EF	9	3	Isom.	Isom.	90	10s	6 x 2	13	-
Sailors and Berg 1987	M	a) b)	12 24	11 9	Squat, Bench press, Curl.	8	3	Weight lift.	Weight train.	55-68-85		3 x 10	a) 20-52 b) 20-35	NS

* Injured subjects at pre-training measurements.

Table 3. Summary of selected resistance training studies in adults. List of abbreviations :

EE : elbow extension
EF : elbow flexion
EMG : electromyography
FT : fast twitch muscle fiber area
FT/ST : ratio of fast twitch fiber area to slow twitch fiber area.
HRT : half-relaxation time
KE : knee extension
KF : knee flexion
IEMG : integrated electromyography
Isok. : isokinetic contraction
Isom. : isometric contraction
Isot. : isotonic contraction
MRTR : maximum rate of torque relaxation
NS : non-significant
RM : repetition maximum
r/s : radian per second
S : significant
ST : slow twitch muscle fiber area
Te : tetanic torque
TPF : time to peak force
TPT : time to peak torque
TT : twitch torque

Table 3. Summary of selected resistance training studies in adults

Reference	Subjects Sex	Age (y)	Num (n)	Muscle train. or exerc.	Dura. (wks)	Freq. (d/wks)	Test. mode	Training mode	Load isot. (% 1 RM or n RM)	isom. (cont. time) (s)	Volume (sets x reps)	Increase in voluntary strength (%)	Contract. propert. (%)	Increase muscle hyper-trophy (%)	Increase fiber hyper-trophy (%)	EMG (IEMG or max EMG) (%)
Berger 1963	M	?	48	Bench press	9	3	Weight lift.	Weight train.	a) 2RM b) 6RM c) 10RM		6 x 2 3 X 6 3 x 10	a) 17 b) 21 c) 20	-	-	-	-
O'Shea 1966	M	?	30	Squat	6	3	Weight lift. Isom.	Weight train.	a) 9-10RM b) 5-6 RM c) 2-3 RM		3 x 9-10 3 x 5-6 3 x 2-3	a) 20 b) 27 c) 22 a) 21 b) 15 c) 23	-	a) 4 b) 5 c) 4	-	-
Moffroid-Whipple 1970	M F	?	6 24	KE	6	3	Isok.	Isok. a) 0.63r/s b) 1.89r/s			1 x 20 1 x 60	a) 8-32 b) 12-20	-	-	-	-
Ikai and Fukunaga 1970	M	23-28	5	EF	14	6	Isom.	Isom.		10s	1 x 3	92	-	23	-	-
Thorstensson et al. 1976	M	19-31	14	Squat	8	3	Dynam. Isom. (KE)	Weight train.	6 RM		3 x 6	67 13	-	NS	-	
Thorstensson et al. 1976	M	22-31	8	Squat	8	3	Dynam. Isom. (KE)	Weight train.	6 RM		3 x 6	73 16	-	2	FT/ST 14	NS
MacDougall et al. 1977	M	19-22	9	Bench press Dips EF	20	3	Isok.	Weight train.	8-10 RM		3-5 x 8-10	28	-	11	-	-
Lesmes et al. 1978	M	24	5	KE KF	8	4	Isok.	Isok. a) 3.14r/s b) 3.14r/s			10x6sec. KE 2x30sec. KF	11-16 12-26	-	NS NS		-
Dons et al. 1979	M	25	18	Squat	7	3	Dynam. Isom.	Weight train.	a) 50 b) 80		1 x 20 1 x 12	a) NS b) NS a) NS b) NS	-	NS	FT/ST NS	-
Lindh 1979	F	27	20	KE	5	3	Isom.	Isok. Isom.		6s	3 x 10	11-32 4-7	-	-	-	-
MacDougall	M	19-24	6	EF	24	3	Isok.	Weight			x 8-10				ST 27	
Moritani and deVries 1979	M F	22 18	7 8	EF	8	3	Isom.	Weight train.	66		2 x 10	36	-	7	-	12
Coyle et al. 1981	M	24	22	KE	6	3	Isok.	Isok. a) 1.05r/s b) 5.24r/s c) mix ve.			5 x 6 5 x 12 2x6-3x12	a) 1-32 b) 15-24 c) 8-24	-	NS NS NS	NS FT 11 NS	-
Caizzo et al. 1981	M F	20-38 20-38	12 5	KE	4	3	Isok.	Isok. a) 1.68r/s b) 4.19r/s			2 x 10 2 x 10	a) 0.5-15 b) 0.4-9	-	-	-	-
Seaborne-Taylor 1981	F	21	15	KE	6	5	Isom.	Isok. a) 1.89r/s b) 0.63r/s			3 x 1 min 3 x 1 min	a) 27 b) 40	-	-	FT/ST -11 FT/ST 17	-
McDonagh et al. 1983	M	19-26	8	EF	5	5	Isom.	Isom.		3-5s	3-5 X 10	20	TT NS TPT NS Te NS	NS	-	-
Kanehisa-Miyashita 1983a	M	24	21	KE	8	6	Isok.	Isok. a) 1.05r/s b) 5.24r/s			1 x 10 1 x 50	a) 7-22 b) -2-20	-	-	-	-
Young et al. 1983	M F	24-48 19-28	6 11	KE	5	3	Isom.	Weight train.	6 RM		3 x 6-8	5-39	-	0.4-12 2-13	-	-
Hakkinen and Komi 1983	M	20-30	14	Squat	16	3	Isom.	Weight train.	80-100 100-120		5 x 1-6 3 x 1-2	21	-	-	-	14
Hakkinen and Komi 1985	M	20-32	11	Squat	24	3	Isom.	Weight train.	70-100 100-120		5 x 5 3 x 1-2	27	TPF 31 (3000N) MRTR NS HRT NS	3	FT 31 ST NS	NS pre-post S 4th-12th week
Duchateau and Hainaut 1984	M F	17-30	20	Adduc. polli.	12	5	Invol.	Isom. Dynam.	30-40	5s	? 10 x 10	-		-	-	-
Davies et al. 1985	M	20-36	7	1st do. inter.	8	5	Isom.	Isom.		10s	8 x 10	33	TT NS TPT NS TR 11	-	-	-
Cannon and Cafarelli 1987	?	?	23	Adduc. polli.	5	3	Isom.	Weight train.	80		1 x 15	15	—	-	-	NS

disparity in results between these studies may well be due to differences in duration and intensity of training.

McDonagh et al. (1983) conducted a study with adult male subjects that was similar in design to the study by Nielsen et al. (1980). Both studies lasted 5 weeks and used isometric training and testing. McDonagh et al. (1983) trained the elbow flexors and used a very high training intensity consisting of 3 sets of 10 contractions lasting 3 to 5 seconds. For the last two weeks, the intensity was increased by further adding two more training sets. In addition, the training frequency was five days per week. The girls in the study by Nielsen et al. (1980) performed 24 isometric contractions of the knee extensors during a 12 minute time period, 3 days per week. The two studies showed that adult males, girls between 13.5 and 19 years of age and girls under 13.5 years of age are capable of making similar relative (%) gains in isometric strength. Other adult studies using isometric training have reported significant increases in isometric strength of 33 % for the first dorsal interosseus (Davies et al. 1985) and of 92 % for the elbow flexors (Ikai & Fukunaga, 1970). The magnitude of change appears to be influenced by the muscle group trained.

The efficacy of isokinetic training for increasing peak torque has been demonstrated in numerous adult studies using the Cybex or Cybex II dynamometer (Moffroid &

Whipple, 1970; Coyle et al., 1981; Seaborne & Taylor, 1981). Investigators have been interested in the study of isokinetic training to determine if it showed velocity specific adaptations (Coyle et al., 1981; Smith & Melton, 1981; Kanehisa and Miyashita, 1983; Jenkins et al., 1984). For this purpose, these studies have trained subjects or contralateral limbs of subjects at different velocities of contraction. In prepubescent studies, Weltman et al. (1986) used hydraulic training which does not represent "true" isokinetic resistance. Since the velocity of training is not known, a precise comparison between this study and adult studies is more difficult. Nevertheless, a comparison can still be drawn since all studies used the Cybex II and specific velocities of contraction for the strength testing. No post-pubescent or adult studies using isokinetic training involved as long a training period as the Weltman et al. (1986) study. The increases in strength reported in the latter study were similar to or higher than any of the studies involving adults. More specifically, knee extension torque in prepubescents, measured at 0.52 and 1.57 $rad \cdot s^{-1}$, increased by 23 % and 19 %, respectively. Smith and Melton (1981) trained 7th and 8th grade students using low (0.52, 1.05 and 1.57) and high velocity (3.14, 4.19 and 5.24 $rad \cdot s^{-1}$) isokinetic training. They reported increases of 21 % for the knee extensors, after low velocity training and a testing velocity of 1.05 $rad \cdot s^{-1}$.

While no adult study measured torque at 1.57 rad·s^{-1}, Coyle et al. (1981) and Kanehisa and Miyashita (1983) observed 32% and 22% increases in knee extensor torque, respectively, at a testing and training velocity of 1.05 rad·s^{-1}. Again, these results indicate that prepubescent subjects are capable of making gains in isokinetic strength comparable to adults.

The use of different testing and training modes has been discussed in the previous section. It was suggested that this factor could explain the poor results obtained by Sewall and Micheli (1986) who used isometric testing to measure strength changes resulting from pneumatic and variable resistance training. One adult study (Dons et al., 1979) observed no significant increase in isometric strength after 7 weeks of squat exercise at 80 % of the 1 RM, while dynamic strength in the squat increased by 36 % (630 N). In two studies where the squat exercise was performed for 8 weeks, Thorstensson et al. (1976a and 1976b) observed significant changes in isometric strength of only 13 % and 16 %, compared to increases of 67 and 73 % in the performance of the squat lift. In most of these adult studies, although dynamic training improved dynamic strength more than isometric strength, significant increases were also reported for the latter. It is likely that the poor results obtained by Sewall and Micheli (1986) are related, in major part, to the low intensity of training used in the study, rather than simply differences in testing and training.

C. Mechanisms of strength increase in adults and prepubescent children

1. Mechanism(s) of strength increase in adults

Increased strength following resistance training in adults has been associated with muscular and neural adaptations (McDonagh & Davies 1984; Komi, 1986). Originally, it was thought that only hypertrophic factors were responsible for increases in voluntary strength, but evidence for neural adaptations following resistance training are numerous (Moritani & deVries, 1979; Hakkinen & Komi, 1983, for reviews, see Sale, 1986 & 1987).

Many adult studies have monitored changes in muscle cross-sectional area using anthropometry (Lesmes et al., 1978; Coyle et al., 1981), ultrasound (Ikai & Fukunaga, 1970; Dons et al., 1979; Young et al., 1983) or computerized axial tomography (O'Hagan, 1987) and fiber hypertrophy using the muscle biopsy technique (Costill et al., 1979; MacDougall et al., 1979; Coyle et al., 1981; Seaborne and Taylor, 1981; Komi et al., 1982; Young et al., 1983). While these studies provide information about the importance of hypertrophic factors in strength increase, they only allow inferences to be made concerning the role of neural adaptations.

Few studies have included direct techniques such as electromyography (Thorstensson et al., 1976; Moritani & deVries, 1979; Hakkinen & Komi, 1983), the interpolated twitch (Caffarelli et al.,), reflex potentiation (Sale et al., 1982; Sale et al., 1983) or firing rate of single motor units (Grimby et al., 1981) to measure neurological adaptations to resistance training.

The contractile properties of muscle have also been studied (McDonagh et al., 1983; Duchateau & Hainaut, 1984) in order to examine the effect of resistance training on the intrinsic characteristics of muscle. Increases in twitch and tetanic tension are independent of cortical or spinal inputs and are associated with an increase in cross-sectional area (Close, 1972).

While two studies have reported an increase in twitch tension with resistance training (Liberson & Asa, 1959; Duchateau & Hainaut, 1984), many investigators have found no change (Davies & Young, 1981, Davies & McGrath, 1982; Sale et al., 1982; McDonagh et al., 1983; Davies et al., 1985). For tetanic tension, only Duchateau and Hainaut (1984) reported a significant increase with training. Two other studies (Davies & McGrath, 1982; McDonagh et al., 1983) observed no training effect on tetanic tension. While Davies et al., (1985) found a significant 11 % increase, after 6 weeks of training, the increase was not significantly different from the control value at the end of the training (8 weeks). The divergence in results between these studies may be due in part, to differences in the duration of training, as well as to differences in muscle groups studied.

The effect of resistance training on the time-related contractile properties of twitch and tetanic contractions is equivocal. Training had no effect on contraction time (CT) and half-relaxation (HRT) (Duchateau and Hainaut, 1984), or time to peak torque (TPT) (Davies and McGrath, 1982; McDonagh et al., 1983; Davies et al., 1985). In contrast, a decrease in CT was observed in two studies (Sale et al., 1983; Alway, 1986). Duchateau and Hainaut (1984) observed increases in both the twitch and tetanic rates of tension and relaxation. Duchateau and Hainaut (1984) concluded that not only can contractile properties be altered by resistance training, but the type of training, in this case, isometric and dynamic training will elicit different results.

Comparing the tension produced by a twitch or tetanic contraction with that of a voluntary isometric contraction provides another method of assessing the relative importance of hypertrophic and neural adaptations in strength increases from resistance training. Several studies have reported lesser increases in evoked strength compared with increases in voluntary stength (Liberson &

Asa, 1959; Sale et al., 1982; McDonagh et al., 1983; Davies et al., 1985).

An even smaller number of studies have attempted to determine the time course of these adaptations by using techniques to make simultaneous measurements of hypertrophy or evoked torque and motor unit activation at predetermined intervals during a resistance training program (Moritani & deVries, 1979; Hakkinen et al., 1981; Hakkinen & Komi, 1983; Hakkinen et al., 1985a). While some studies have suggested that the early changes in strength are accounted for largely by neural adaptations with a gradually increasing contribution from hypertrophic factors (Moritani & deVries, 1979; Hakkinen et al., 1981; Hakkinen & Komi, 1983), others have observed the manifestation of both adaptations in the early stages of training (Hakkinen et al., 1985a).

The adults studies discussed above suggest that the time course of neuromuscular adaptations responsible for strength increases has not yet been established with certainty. Differences in results among these studies may depend on a number of variables discussed below.

First, subjects that are untrained are capable of greater initial gains in strength than weight trained athletes (Hakkinen & Komi, 1983; Hakkinen, 1985). In the case of experienced weight trained athletes the size of the muscle fiber may show little increase with training, having already reached an optimal capacity for enlargement (MacDougall et al., 1982). Neural adaptations may also be less important since there is evidence of greater activation (Sale et al., 1983) and synchronization (Milner-Brown et al., 1975) of motor units with this group.

Second, the specific intensity and mode of training used during a particular phase of the training program may favor certain adaptations over others (Hakkinen & Komi, 1983; Hakkinen, 1985). The use of either isometric, concentric or eccentric contractions for short term training brought about similar increases in strength (Hakkinen & Komi, 1981). In training of a longer duration, a combination of mostly concentric contractions supplemented with eccentric contractions gave a greater increase in maximal strength (Hakkinen & Komi, 1981). Greater improvement in muscle activation measured by IEMG was observed between the 4th and 12th week of a 24 week training program, when the training load was increased from between 70 to 80 % of the 1 RM (week 1 to 4) to between 80 to 110 % of the 1RM (Hakkinen & Komi, 1985). However, the increase in strength observed between the 16th and 24th week was lower, even if a comparable intensity was used (80 to 120 % of the 1 RM). Some decrease in muscle activation was observed during that latter period.

This provides evidence that other factors such as the duration of training, the sequencing of the intensity cycles and the number of intervals chosen for the measurement of the dependent variables must also be considered for an accurate description of the time course of neuromuscular adaptations (Hakkinen & Komi, 1986).

Finally, the particular muscle trained may also be a factor influencing the manifestation of these adaptations. Muscles that are not usually subjected to any resistance, may exihibit a higher training response. Variation in fiber distribution from one muscle to the other could be a determinant of muscle strength (Dons et al., 1979). A muscle with a higher % of FT fibers could display a greater increase in strength since there is evidence that resistance training preferentially increases FT fiber area (MacDougall et al., 1980). Lastly, there is still some controversy regarding the measuring techniques used to assess these adaptations. The effect of changes in subcutaneous fat and fiber hypertrophy on the EMG signals is not clearly understood (Young et al., 1983; Cannon & Caffarelli, 1987). The increase in EMG may be due in part to larger amplitude potentials of hypertrophied muscle fibers (Sale, 1987). While some studies have found a linear relationship between EMG and force, others have found a positively accelerating relationship with increasing force (Bigland-Ritchie, 1981). The discrepancies between these results could be due to the particular muscle group used, differences in the experimental procedures such as electrode type, size or placement or distortions caused by the recording techniques (Bigland-Ritchie, 1981). The use of standardized equipment and procedures would enable unequivocal comparisons of results to be made from one study to another (Moritani & Muro, 1987). Techniques estimating muscle or fiber cross-sectional area have also been criticized because of their lack in accuracy; the muscle fiber biopsy technique (Eisenberg, 1984), anthropometric girth measurements (Young et al., 1983) and ultrasonography (Haggmark et al., 1978).

2. Mechanism(s) of strength increase in prepubescent children

It is difficult to assess the relative importance of the mechanisms discussed above, since no study dealing with prepubescent resistance training has directly addressed this issue. Only four studies have attempted to observe the effect of resistance training on muscle cross-sectional area during prepubescence (Vrijens, 1978; McGovern, 1984; Weltman et al., 1986; Funato et al., 1987).

Vrijens (1978) used soft-tissue roentgenography to determine the effect of 8 weeks of weight training on the upper-arm and thigh of prepubescent and post-pubescent boys. This technique is normally used to determine fat thickness and usually no direct measurement of muscle cross-sectional area is made from these x-ray pictures

(Haggmark et al., 1978; Hudash et al., 1985). While no details were given, Vrijens (1978) possibly measured muscle cross-sectional area by determining the area delimited by the subcutaneous fat layer and substracting this area from the area of the whole limb, to derive lean area. This could explain why both fat and muscle cross-sectional area results are reported in the study. It is not clear if the measured "muscle" area includes the bone and lean muscle area or if the bone area was substracted. While the precise method by which muscle cross-sectional area was determined remains unclear, this study offers the most accurate assessement to date of changes in muscle size in prepubescent and post-pubescent children following resistance training.

The results showed that prepubescent boys made no increase in muscle cross-sectional area, while the post-pubescent males increased thigh and upper-arm cross-sectional area by 5 and 14 % respectively. While strength did not improve in the extremities for the younger group, post-pubescent males made significant gains in elbow flexor (17 %) and extensor (33 %) and knee flexor (32 %) and extensor (19 %) isometric strength.

The studies of McGovern (1984) and Weltman et al. (1986) used anthropometric measure of limb girth to determine changes in muscle cross-sectional area. McGovern's study, published as an abstract, found no increase in girth of the arm despite increases in performance strength for the bench press, arm curl and chin-ups exercises.

Similar results were reported by Weltman et al. (1986) which led to the conclusion that the increase in strength was the result of neural adaptations. This conclusion would be consistent with the observation in adults of a substantial increase in maximal voluntary strength, during the early phase of training (8 weeks) which is largely independent of changes in muscle cross-sectional area (Liberson & Asa, 1959; Ikai & Fukunaga, 1970; Dons et al., 1979; Moritani & deVries, 1979; MacDougall et al., 1980). Results from the study by Funato et al. (1987) should beinterpreted with caution. While significant changes in elbow extensor area between 10 to 25 % were observed for three groups of boys and girls (7, 9, 11 year olds), the elbow flexors in which the maximum training effect was expected showed smaller increases (between 11 to 15 %) and only for the 11 year olds. Other suspicious results included significant increases in bone size of 31 to 38 % and an increase in isometric strength of the antagonist elbow extensors, which was three times higher than that of the agonist elbow flexors. These results raise questions regarding the appropriateness of study design and methodology and the accuracy of the ultrasound technique to determine muscle cross-sectional area.

Another issue of concern is the possible role of endocrinologic influences on neuromuscular adaptations to resistance training in this population. Androgens are thought to play an important role indifferentiating muscularity and strength performances between sexes. Testosterone and androstenedione are the most important circulating androgens, being secreted at the rate of 5-10 mg/day and 1-2 mg/day in adult males, respectively (Lamb, 1975). In adult females, the secretion of testosterone is very low compared to males (0.1 mg/day) while that of androstenedione is higher (2-4 mg/day) (Lamb, 1975). One reason why males increase their muscle mass more easily than females, is that testosterone is five times more anabolic than androstenedione. Resting levels of testosterone in prepubescent boys (Tanner stage 1) are usually lower than 50 $^{n}g \cdot dl^{-1}$ (Winter, 1978). In prepubescent boys and girls the levels of circulating androgens are similar so that any differences in strength performances between the sexes cannot be attributed to hormonal influences (Winter, 1978).

Studies have examined the acute hormonal responses of adult males and females to bouts of weight training, since it was suggested these responses could facilitate or enhance muscle hypertrophy. The half-life of testosterone in the human has been established at 6.6 minutes, 33 minutes and 3.4 hours depending on the metabolic pools (Lamb, 1975). Therefore, increases in testosterone following acute training could enhance muscle hypertrophy. Studies have reported an increase testosterone level immediately after weight training in males, but not in females (Fahey et al., 1976; Weiss et al., 1983). Whether the higher level of testosterone in males provides an advantage for greater increased in hypertrophy following resistance training remains to be demonstrated (Weiss et al., 1983). To the author's knowledge, no studies have examined the acute response of androgens to resistance training in prepubescent children.

Following acute sessions of weight training, increases in growth hormone (Vanhelder et al., 1984), cortisol, and glucagon (Vanhelder et al., 1985) have been observed in adult men. The effect of acute increases of these hormones is beyond the scope of this thesis, the reader is referred to extensive reviews of this topic (Galbo, 1981; 1983).

The effect of longitudinal resistance training on hormonal response has been investigated in adult males (Hakkinen et al., 1985) and females (Fahey et al., 1976; Hetrick & Wilmore, 1979; Westerlind et al., 1987). Hakkinen et al. (1985) found a significant correlation between changes in isometric strength and the change in the testosterone\cortisol ratio. The ratio increased during the first 16 weeks of training with increasing gains in strength. In the last four weeks, individual variations in strength were observed, with some subjects continuing to increase in strength, while others lost strength. Again the testosterone\cortisol ratio had a high correlation with the magnitude of the individual change in strength. The measurement of this ratio is of interest since testosterone produces an anabolic effect, while cortisol, a glucocorticoid, inhibits hexokinase, and increases gluconeogenesis and protein catabolism. A correlation was also found between isometric strength and changes in the testosterone\sex hormone-binding globulin (SHBG) ratio which determines the level of biologically active unbound testosterone.

In contrast, no relationship was found between serum testosterone and strength in females following resistance training (Fahey et al., 1976; Hetrick & Wilmore, 1979; Westerlind and al., 1987). No significant difference was found for androstenedione and SHBG after 12 weeks of hydraulic resistance training (Westerlind and al., 1987). With prepubescent boys, Weltman et al.(1986) reported no significant changes in testosterone levels after 14 weeks of hydraulic resistance training.

Obviously testosterone is not the only important factor regulating muscularity and strength development.

Some females will display strength performance comparable to males, despite having normal and lower testosterone levels compared to males (Fahey et al., 1976). Many studies training female subjects have reported significant increases in strength following resistance training (Brown & Wilmore, 1974; Krotkiewski et al., 1979; Seaborne & Taylor, 1982; Kaufman, 1985; O'Hagan, 1987). Increases in muscle size (Wilmore et al., 1978; Krotkiewski et al., 1979) have also been reported with this population. In a recent study (Cureton et al., 1988), both males and females made comparable gains in absolute strength of elbow and knee flexion. An even more surprising results is that absolute changes in cross-sectional area, measured by CAT, were not significantly different between the sexes.

There is also evidence from animal studies that an increase in work-induced hypertrophy can take place in hypophysectomized animals (Goldberg et al., 1975). Whether human males, deficient in testosterone are capable of making gains in muscle hypertrophy is not known. No correlation has been found between testosterone level and muscle mass in humans. While androgens appear to be involved in developmental growth (Goldberg, 1975), their possible role in muscle hypertrophy with resistance training remains to be shown.

Based on the existing literature, it is difficult to provide an unequivocal statement about the importance of muscle hypertrophy for strength increases in prepubescent children following a program of resistance training. Weltman et al. (1986) found that chronic resistance training had no effect on the level of circulating androgens, although significant gains in strength were achieved by the prepubescent boys. This may suggest that androgens only play a secondary role, if any in increasing strength or muscle hypertrophy in this population.

In summary, the mechanism(s) underlying strength gains following resistance training during prepubescence remain largely unexplained. A few studies, utilizing anthropometric techniques, have reported no significant increases in muscle cross-sectional or lean area of the extremities following resistance training programs of varying duration and intensity. No study to date, with the exception of the study by Weltman et al. (1986), has investigated the relationship between concurrent hormonal and neuromuscular adaptations to resistance training in this population, and the possible importance of hormonal responses in regulating muscularity and strength performance with training during childhood remains to be determined. Due to methodological constraints, strength increases following resistance training during childhood have, by the process of elimination, been attributed to rather vague and undefined neurological adaptations. The precise nature and importance of neurological adaptations to strength increases with resistance training during childhood remains to be determined.

Chapter III

Methods

Subjects

The boys, aged 9-11 years, were volunteers recruited from 4 grade schools in the Hamilton Separate Catholic School Board. The experimental group (n = 13) was drawn from one school and the control subjects (n = 13) from three other schools. Subjects and parents were informed both in writing and orally about the objectives and scope of the study . Informed consent was obtained from both the children and parents in accordance with the policies of the Ethics Committee of McMaster University. All boys had a medical examination and an assessment of maturity level (Tanner pubic hair stages, Tanner, 1962) by a physician. Two exclusion criteria were used: 1) children with chronic pediatric disease or orthopedic disability and 2) children who were not classified as Tanner stage 1 at the beginning of the study.

Experimental Treatment

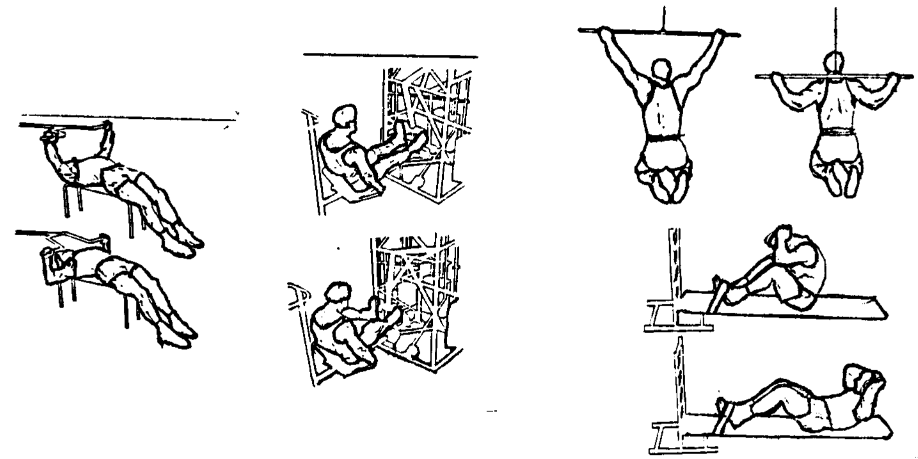
Resistance training was done by the experimental group using a circuit training approach. With this method, the subjects performed one set of a specific exercise at a station before moving to the next station. The frequency of training was three sessions per week with each session lasting 50 to 60 minutes. These sessions were conducted under supervision at the school during the lunch period. Most children trained on Mondays, Wednesdays and Fridays, so that the days of training were interspersed with rest days. However, training sessions were also available on Tuesdays and Thursdays for those who had missed or could not attend the regularly scheduled training sessions.

Specifically, the training (Table 4) consisted of five sets for the primary exercises (preacher arm curl and double leg extension) and three sets for the secondary exercises (leg press, bench press and behind the neck pulldown). In addition, abdominal exercises (sit-ups or trunk curl) were done to strengthen the mid-section. The purpose of the primary exercises was to provide specific overload to the two major muscle groups of interest in this study, namely, the elbow flexors and knee extensors. The secondary exercises were included to provide a general conditionning effect. Training was performed in two phases, each phase lasting 10 weeks.

Two recreational activities were scheduled for the control group. These activities were not related to strength training. The first activity consisted of bowling, and 10 of the 13 subjects took part. The second activity was recreational swimming, and 11 of the 13 control subjects took part. The bowling and swimming sessions were separated by 2 months and both sessions were supervised by

Table 4. Training regimen, including frequency, duration, method, volume and load of training.

FREQUENCY : 3 TIMES\WEEK
DURATION : 20 WEEKS
METHODS : CIRCUIT TRAINING



PHASE 1

SETS : 5	SETS : 3
REPS : 10, 3 x 10–12 RM, 1 x MAX	REPS : 10, 2 x 10–12 RM
LOAD (% 1 RM) : 60, 3 x 70–75, 60	LOAD (% 1 RM) : 60, 2 X 70–75

PHASE 2

SETS : 5	SETS : 3
REPS : 10, 3 x 5–7 RM, 1 x MAX	REPS : 10, 2x 5–7 RM
LOAD (% 1 RM) : 60, 3 x 80–85, 75	LOAD (% 1 RM) : 60, 2 x 80–85

the training staff. No attempt was made to change dietary or activity patterns for either the control or the experimental group during the study.

Phase 1

Five and three sets of 10-12 repetitions were performed respectively for the primary and secondary exercises. The first and fifth sets for the primary exercises and the first set for the secondary exercises were executed at 60 % of the previously and individually determined one repetition maximum (1 RM). Ten repetitions were performed for the first set serving as a warm-up for both groups of exercises. The second, third and fourth sets of the primary exercises and the second and third sets of the secondary exercises were done to failure at a load of 70-75 % of the predetermined one RM. The fifth set of the primary exercises was done to failure. When the subject could perform 12 repetitions on each of the intermediate sets, the training load was increased by either 0.454 kg (1 lb.) or by 0.682 kg (1.5 lb.), the smallest weight increments provided by the equipment manufacturer (Rubicon Inc.).

Phase 2

In order to increase the overload on the muscle, the intensity of the first training session of the week was increased. This was accomplished by increasing the load of the second, third and fourth sets of the primary exercises and the load of the second and third sets of the secondary exercises to between 80-85 % of the 1 RM. The first set for each group of exercises was kept at 60 % of the 1 RM, while the fifth set of the primary exercises was increased to 75 % of the 1 RM. All but the first set of each exercises were performed to failure. The training load was adjusted using similar weight increments as in phase 1 when the subjects exceeded 7 repetitions for any exercise beyond the first set. The intensity of the other weekly sessions was the same as in phase 1. At the end of each week the training diary was reviewed by an instructor and the resistance was adjusted if necessary according to the previously mentioned guidelines. Under adult supervision the children were responsible for recording the number of repetitions completed for each exercise at the predetermined loads. The subject-supervisor ratio was no greater than 4-1.

Methods of Measurements

Table 5 outlines the measurements made during the study. They consisted of : A) voluntary strength measurements, B) evoked contractile properties, C) % motor unit activation using the interpolated twitch technique, D) muscle cross-sectional area using computerized axial

Table 5. Measurements for resistance training study including A) voluntary strength, B) electrically evoked contractile properties, C) interpolated twitch, D) muscle cross-sectional area and E) anthropometry and body composition.

A) VOLUNTARY STRENGTH :

1) 1 REPETITION MAXIMUM : bench press and leg press

2) MUSCULAR ENDURANCE : bench press and leg press

	Elbow flexors	Knee extensors
3) ISOKINETIC STRENGTH :	0.52.1.05,2.09,3.14 $rad \cdot s^{-1}$	0.52,1.05,2.09,3.14 $rad \cdot s^{-1}$
4) ISOMETRIC STRENGTH :	80°,100°,120°,150°	90°,120°,140°,160°
B) ELECTRICALLY EVOKED CONTRACTILE PROPERTIES :	80°,100°,120°,150°	90°
C) INTERPOLATED TWITCH :	100°	90°

D) MUSCLE CROSS–SECTIONAL AREA

E) ANTHROPOMETRY AND BODY COMPOSITION

tomography and limb girth (arm only) and E) anthropometry and body composition.

A) Voluntary Strength

Voluntary strength was measured using the following testing modes : 1) One repetition maximum performance strength was measured on a global Gym station for double leg press and bench press. Performance for the double arm curl and the double leg extension was assessed for the experimental group only on the training device because of logistical concerns. An initial warm-up of 3-7 repetitions was given for each exercise. For the pre-testing the one RM was found within 6-8 repetitions by increasing the load by large increments to begin with and then using increments of 2.5 to 1.25 kg to precisely identify the 1 RM. For the mid- and post-testing, the previous values from the pre- and mid-testing respectively were used as guidelines to establish the new one repetition maximum value. For both the mid- and the post-testing, the warm-up consisted of 3-7 repetitions at 50-80 % of the previously determined 1 RM. Two to three single repetitions done at 80-95 % of that previously determined one RM were then performed. If these were successful the previous one RM was attempted. If this lift was successful, the resistance for the next trial was increased by increments of 1.25 to 5 kg depending on how easily the previous lift had been achieved. When the lift could not be completed the load was decreased by 1.25 kg until it was completed. A minimum rest period of 2 minutes was given between each trial. Excluding the warm-up, the new 1 RM was achieved within 6-8 trials.

2) Muscular endurance was measured for both groups by having subjects perform as many repetitions as possible with the pre-test 1 RM for the bench press and leg press. The same procedure was repeated for the double arm curl and the double leg extension for the experimental group only.

3) Peak isokinetic voluntary strength was measured using an isokinetic dynamometer (Cybex II, Ronkonkoma, NY) for the right arm elbow flexors and right leg knee extensors. Peak torque was the greatest torque developed during the contraction after the impact torque (Sale, 1982). It was recorded at four velocities : 0.523, 1.046, 2.094 and 3.141 $rad \cdot s^{-1}$. The undamped torque signal from the Cybex transducer was displayed on one channel of an oscillograph recorder (Hewlett-Packard 7402a, San Diego, CA). For the elbow flexors, the subject was seated with his right upper arm parallel to and resting on a padded table. The shaft of the Cybex was aligned with the axis of the right elbow joint. The end of the adjustable lever arm had a handle that the subject grasped with the forearm supinated. An assistant placed a hand on the shoulder of the subject to provide stabilization and to prevent any movement of the

upper body. The subject's left hand remained motionless on the lap. The subjects began the contraction with the elbow fully extended and continued the contraction through the greatest possible range of movement.

For the knee extensors, the subject was seated on a padded chair, especially designed for this purpose. The hip was extended at an angle of approximately 120° during these measurements. The subject was strapped across the chest, the hip and the right thigh. The lower right leg was secured to a pad attached to the Cybex shaft by a metal arm. The Cybex shaft was aligned with the axis of the right knee joint and the same lever arm length was used for the pre-, mid- and post-measurements. The subject began the contraction with the knee at a joint angle of 90° (full extension : 180°) and continued the contraction until full extension was achieved. Three sub-maximal warm-ups preceded three trials at each velocity. A rest interval of 15 to 30 s was given after each trial. The average of the best two trials at each velocity was used for the analysis of the results. The order of testing for the elbow flexors and the knee extensors was counterbalanced. The 4 velocities of contraction were randomized.

4) Peak voluntary isometric strength was measured on custom made dynamometers by recording torque at 4 joint angles for the right arm elbow flexors (80°,100°,120° and 150°; 180°

was full extension) and 4 joint angles for the right leg knee extensors (90°,120°,140° and 160°; 180° was full extension). For the elbow flexors, the right upper-arm rested on an horizontal steel plate and the forearm in the supinated position, on a second plate connected to the first one by a steel shaft. The steel shaft of this axis was equipped with a torque transducer consisting of foil strain gauges. By securing the forearm to this second plate, isometric contractions could be developed at various angles around the elbow joint. The torque signal from the transducer was amplified by a custom-made amplifier and converted to a digital signal. The amplified signal was visualized on a storage oscilloscope (Hewlett-Packard 120 1B, San Diego, CA) and analyzed by a computer (PDP 11-03, Digital Equipment Corp., Maynard, Mass.). The subject was seated facing the dynamometer and the upper-right arm was aligned with the shoulder joint. The left arm was secured to the left thigh to prevent bracing during the trial. In order to isolate the contraction of the elbow flexors, a strap also secured the right shoulder to the arm of the chair. To further prevent interference by the shoulder or the rest of the upper body, an assistant placed one hand on the shoulder of the subject, applying downward pressure and held on to the strap.

For the knee extensors, the right lower leg was secured by a velcro strap to a steel support. The support was attached to a heavy duty steel chair by a shaft that could rotate around the axis of the knee. Like the arm device, a transducer attached to the steel shaft recorded the torque. This output was sampled and treated in a similar manner to that for the elbow flexor dynamometer. The subject was seated at a hip joint angle of 120° and was secured to the steel chair by three straps : one across the right thigh, one across the hip and one across the chest. The subjects were also reminded before each new trial to keep their arms crossed over their chest and to keep their left leg motionless. In all cases, arm testing preceded leg testing. The 4 angles were randomized for both arm and leg testing. Two trials were done for each angle and an average of the two was used for the analysis of the results.

B) Electrically Evoked Contractile Properties

Twitch contractions of the right arm elbow flexors were measured at the same joint angles and using the same dynamometer used for the determination of the isometric peak torque. The order of testing for joint angle was randomized. The twitch contractions were evoked through percutaneous stimulation. Rubber electrodes impregnated with conductance gel were taped on the forearm just distal to the elbow fossa (anode) and on the belly of the biceps over the motor point (cathode). Because of greater discomfort, the evoked twitch contractions for the right leg knee extensors were measured only at the 90° joint angle. The rubber electrodes were placed just proximal to the patellar tendon over the vastus and rectus femoris (anode) and over the femoral nerve beside the femoral artery in the pelvic notch (cathode).

Stimuli were rectangular voltage pulses of 100 to 200 us duration, produced by a Devices stimulator (Medical System Corp.). The voltage was increased in a step-wise fashion until the twitch torque viewed on channel A of the oscilloscope could not be increased further. This was considered to be the maximum twitch response. Two trials were given and the converted torque signals were fed into a computer (Digital Equipment Corp., Maynard, Mass). The average of the two trials was used for the analysis of results. The voltage intensity ranged between 100 to 200 volts for the arm and between 200 and 400 volts for the leg.

Torque (N·m), time to peak torque (ms), 1/2 relaxation time (ms) and maximum rate of torque development and relaxation ($N.m \cdot s^{-1}$) were measured using a custom programmed software package. The twitch contractions were measured before the isometric MVCs to avoid potentiation effects.

C) Interpolated Twitch

The interpolated twitch technique (Denny-Brown, 1928; Merton, 1954; Belanger and McComas 1981) was used to assess the degree of motor unit activation at a joint angle of 100°, for the right arm elbow flexors, and 90° for the right leg knee extensors. With this technique a supra-maximal stimulus (twitch) is delivered to the muscle at the peak of a maximal voluntary contraction. If the subject does not fully activate the motor unit pool, an increment in torque over the peak torque produced by the MVC will be visible on channel B of the oscilloscope at the time of twitch stimulation. A photograph of the interpolated twitch tension was taken from the oscilloscope and the number of divisions along the vertical axis of channel B was counted. Each big division could be broken down into 5 smaller divisions, giving a precision of up to 10^{-1} divisions. Each division was calibrated to 33.7 and 16.7 N·m per division for the elbow flexors and knee extensors, respectively. In order to convert the number of divisions to torque, the gain in volts per division was divided by the appropriate calibration factor and multiplied by the number of divisions calculated from the photograph. The % motor unit activation (MUA) was determined using the following formula:

$$\% \text{ MUA} = \frac{(\text{RTT} - \text{ITT})}{\text{RTT}} \times 100 \%$$

in which RTT = resting twitch torque and ITT = the interpolated twitch torque. Two trials were recorded for each limb and the highest one was used as the criterion score.

D) Muscle and Lean Cross-Sectional Area

Muscle cross-sectional area of the right mid-upper arm between the acromion and the olecranon processes and of the right mid-thigh between the pubic symphysis and the medial condyle of the femur were measured using computerized axial tomography-CAT scan (fourth generation high resolution Ohio Nuclear 20/20 series scanner). A single scan was taken for each limb. Negative photographic slides were taken of the CAT scan prints and area measurements were determined by manual planimetry using a computerized digitizing platform (Compucolor Inc.). Total cross-sectional area, total lean area, flexor area, extensor area and the bone area were measured. The CAT scans were analyzed in a double blind fashion with the examiner being unaware of either subject group placement (experimental vs control) or testing condition (pre vs post).

Lean cross-sectional area of the mid-upper right arm was also determined by measuring the circumference and the anterior, posterior, medial and lateral skinfolds at the same site used for the CAT scan measurements (mid-way between the olecranon and acromion processes). Based on the skinfolds and circumference measures, lean cross-sectional area was calculated using the method described by Moritani and deVries (1980). For both CAT scan and circumference measurements, the arm was in a fully extended resting state. CAT scans of the thigh were taken with the leg fully extended and resting.

E) Anthropometry and Body Composition

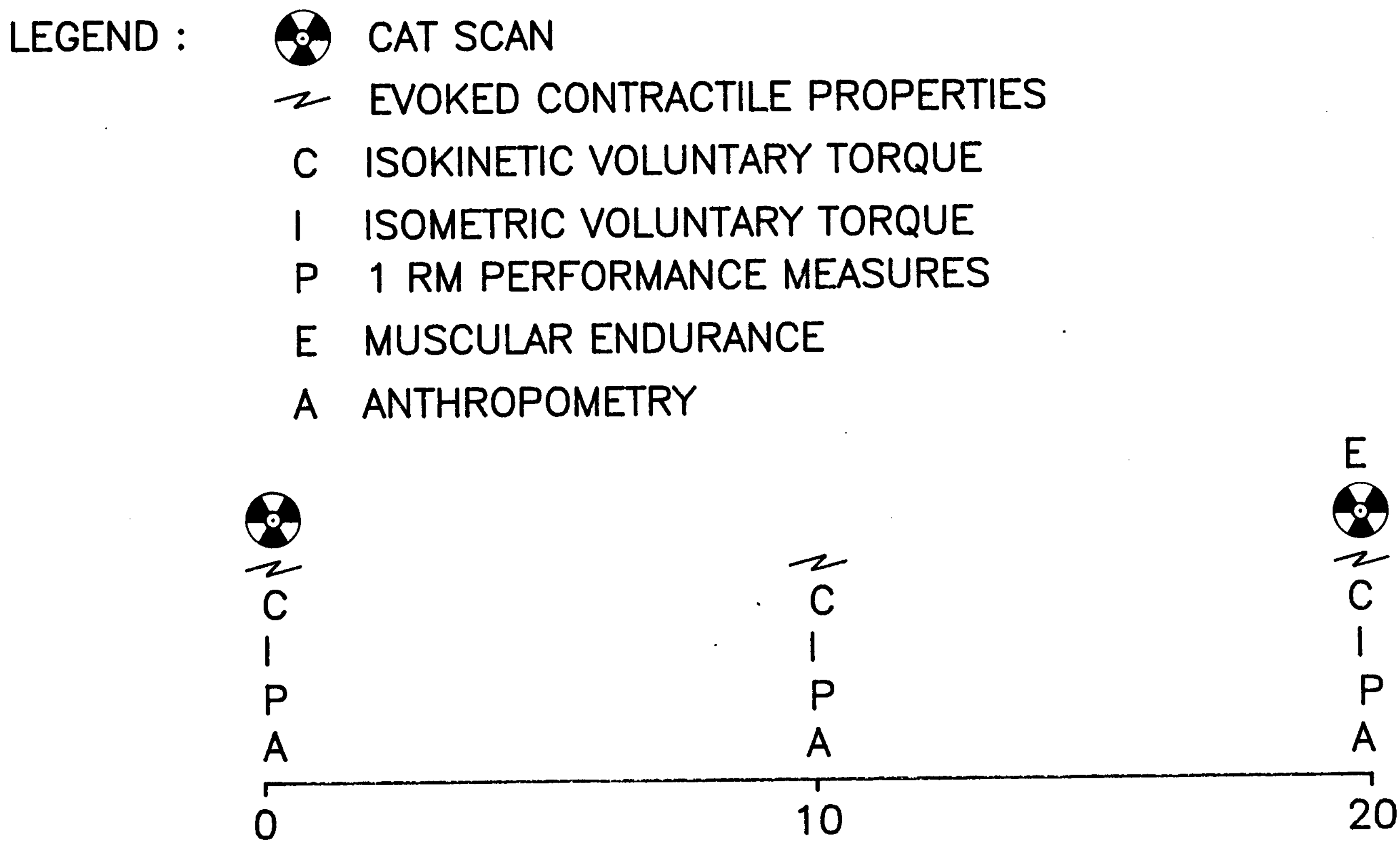
Skinfolds were measured at the following sites on the right side of the body using a Harpenden skinfold caliper : suprailiac, subscapular, triceps and biceps. Percent body fat was determined using the equation of Lohman et al., (1984). Standing height was measured with subjects in their bare feet and weight was measured with subjects wearing only their shorts. All anthropometric measurements were made by the same investigator.

F) Time-table

Figure 1 gives the time course for the measurements during the study. With the exception of weight, height, muscular endurance and CAT scan all the other measurements were taken at the beginning, mid-point (after 10 weeks) and end of the study. Weight, height and CAT scan were measured only at the beginning and end of the study. Muscular endurance was measured only at the end of the study. For

Figure 1. Time-course for the testing of the dependent measures, including isometric (I) and isokinetic (C) maximum voluntary contraction, evoked contractile properties (✓), performance measures (P), CAT (●), muscular endurance (E) and anthropometry (A).

TIME—COURSE OF DEPENDENT MEASURES



both the mid-point and the post-testing, two to three days of rest were allowed before the strength testing sessions to eliminate acute fatigue resulting from the training.

Statistical Methods

The strength results are presented first in absolute units, and then in relative units per square centimeter of flexor and extensor area for the elbow flexors and knee extensors, respectively. Various statistical analyses were used including :

1) Two and three way analysis of variance (ANOVA) with one or two repeated measures respectively, to determine the significance of the effect of training on the dependent variables. The dependent variables included strength, morphology, contractile properties, anthropometry and physical characteristics. A two-way ANOVA with one repeated measure was also used to determine if the transfer of the strength gain from the weight training was comparable for three modes of testing and the twitch torque measurements.

The following gives a detailed example of the procedure utilized to determine main effects and identify significant differences among means for a three way ANOVA with two repeated measures for maximum voluntary isometric peak torque (dependent variable) of the elbow flexors. The between subject factor is treatment made up of two levels : experimental and control. The repeated (within) subject factors are : (1) time with 3 levels ; pre-, mid- and post-training and (2) joint-angle with 4 levels ; 80°, 100°, 120° and 150°.

Table 6 shows how the three factors interact. The following interactions were examined and depending on the results (significant or insignificant interaction), a post hoc Tukey test (2 mean comparison) was used to identify significant differences among means :

a) treatment x angle x time : a significant interaction indicated that there was a training and/or growth effect on the dependent variable at either the mid- and/or post-test and for either one, two or three of the four joint angles of contraction.

Post hoc : means (n=24) were compared in order to determine at which testing time-joint angle combination, training and/or growth had a significant effect. The three following outcomes were considered :

1) A significant difference between the 3 means (pre-, mid- and post-training), at a joint angle, in the control group, was interpreted as a growth effect for that joint angle.

2) A significant difference between the 3 means (pre-, mid- and post-training), at one joint angle, in the experimental group, without a growth effect at that same joint angle (insignificant difference between the three

Table 6. Example of a three-way ANOVA with two repeated (within) measures.

Between factor : treatment
Repeated factor #1 : angle
Repeated factor #2 : time

BETWEEN	FACTORS REPEATED				
TREATMENT	TIME	ANGLES			
		80°	100°	120°	150°
EXPERIMENTAL	PRE	INDEPENDENT VARIABLE :			
	MID				
	POST				
CONTROL	PRE	TORQUE			
	MID				
	POST				

means, at that joint angle, for the control group) was interpreted as a training effect.

3) If a significant difference was obtained between the three means (pre-, mid- and post-training), at one joint angle, for both the experimental and control group, the means from the 2 groups were compared with each other. Only, if the experimental and control groups had similar pre-training means and the experimental group had significantly greater mid- and/or post-training means than the control group, for that joint angle (e.g. 80°) was the difference between groups attributed to a training effect. If the interaction was not significant, the treatment x time interaction was considered.

b) treatment x time : a significant interaction, without a treatment x angles x time interaction, indicated that there was a training and/or growth effect on the dependent variable at either the mid- and/or post-test for all four joint angles of contraction.

Post hoc : means (n=6) were compared in order to determine at which testing time, training and/or growth had a significant effect. Three outcomes were possible :

1) A significant difference between the 3 means of the control group was interpreted as a growth effect.

2) A significant difference between the 3 means of the experimental group with no growth effect (insignificant

difference between the 3 control means) was interpreted as a training effect.

3) If a significant difference was found between the 3 means of both the experimental and control group, the means from the 2 groups were compared with each other. Only, if the experimental and control groups had similar pre-training means and the experimental group had significantly greater mid- and/or post-training means than the control group, was the difference between the groups attributed to a training effect. If the interaction was not significant, the time factor was considered.

c) time : a significant time interaction, without a significant treatment-time interaction, indicated that there was a growth effect.

Post-hoc : means (n=3) were compared in order to determine at which testing time, growth had a significant effect.

2) The Friedman two-way analysis of variance, a non-parametric statistic was used to determine the significance of the effect of training on the % motor unit activation.

Reliability

Independent projects were conducted to assess the reliability of the measurement techniques used in this study. Details on the methodology are given in appendices

A, B and C. First, the day to day and trial to trial reliability of the voluntary strength and evoked contractile property measurements were assessed, using 6 prepubescent subjects from the study.

Second, a site to site reliability of the computerized axial tomography technique was conducted on the right upper-arm and thigh of adult subjects. In addition, the accuracy of the technique was assessed by scanning phantoms and comparing their actual surface with the area derived from the scan negatives. Finally, intertester reliability of the digitizing procedure used to assess cross-sectional area from computerized axial tomography was measured.

Chapter IV

Results

A. Anthropometric and Cross-sectional Characteristics

There were no significant differences in height, weight, or sum of two skinfolds (triceps and subscapular) between the experimental and the control groups initially or after training (Table 7). Weight (+4.2 %, $p<.01$) and height (+0.6 %, $p<.01$) were significantly increased by growth.

There was a significant growth effect on the sum of 4 circumferential skinfolds of the right upper arm and thigh. There was a significant training (+3.9 %, $p<.05$) and growth (+2 %, $p<.05$) effect for arm girth, but lean arm cross-sectional area (CSA) estimated from the girth and the circumferential skinfolds was not affected by training or growth. No training effect was evident for any of the cross-sectional areas, measured by computerized axial tomography-CAT scan, for the right upper-arm or thigh (Figure 2). There was a significant growth effect for arm lean area (+2.6 %, $p<.05$), arm flexor area (+7.7 %, $p<.05$), total thigh area (+6.2 %, $p<.01$), lean thigh area (+5.3 %, $p<.05$) and thigh extensor area (+8.1 %, $p<.05$).

In the reliability study (appendix B), using adult subjects, when a 2 centimeter difference in site was chosen

Figure 2. Cross-sectional characteristics of right upper-arm and thigh pre- and post-training. Figures are : A) lean CSA of the arm B) elbow flexor lean CSA C) lean CSA of the leg and D) knee extensor lean CSA. Hatched and blank bars represent mean ± SE of the experimental and control group, respectively. Growth effect τ $p<.05$.

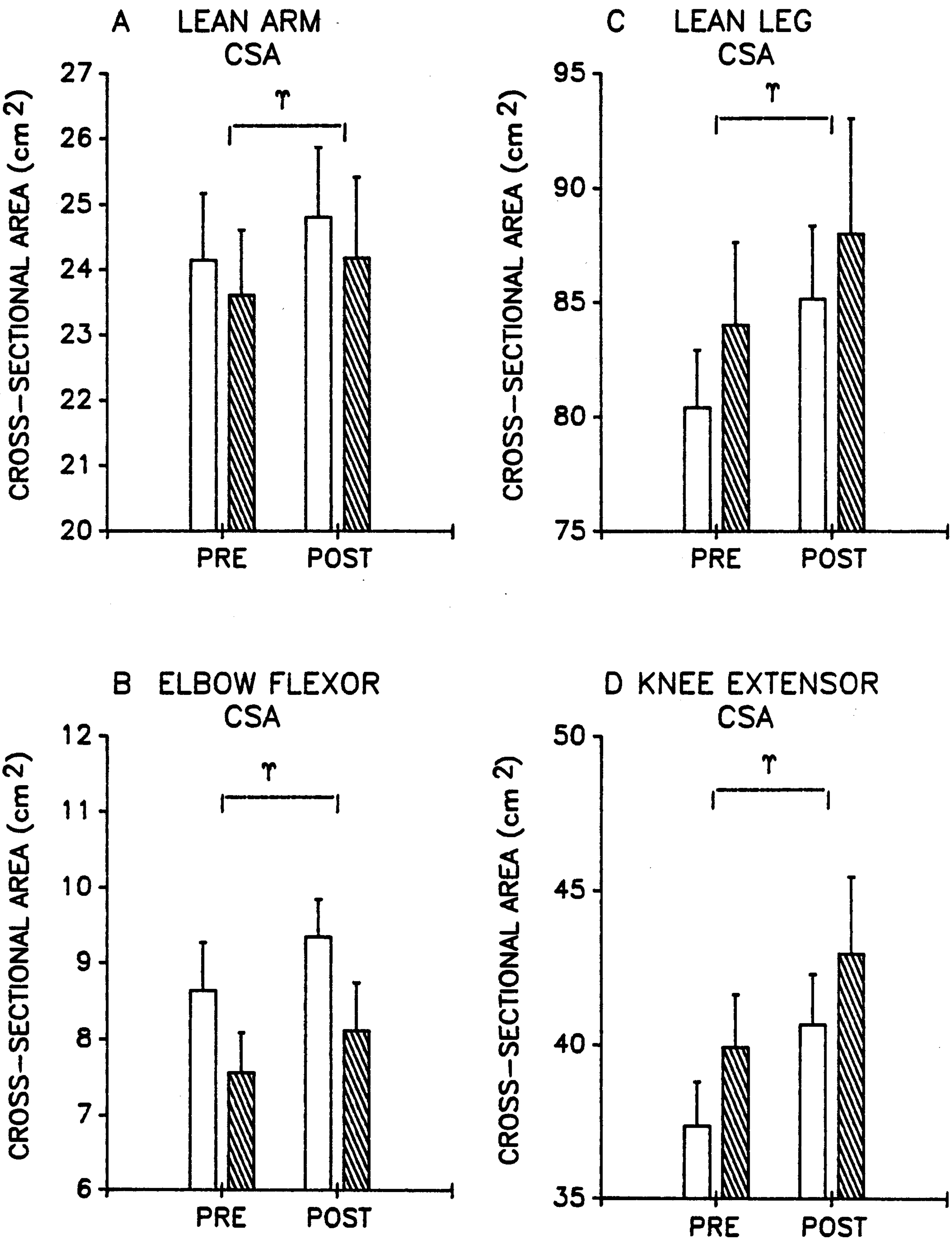

A LEAN ARM
CSA
CROSS-SECTIONAL AREA (cm 2)
27
26
25
24
23
22
21
20
PRE
POST
C LEAN LEG
CSA
95
90
85
80
75
B ELBOW FLEXOR
CSA
12
11
10
9
8
7
6
D KNEE EXTENSOR
CSA
50
45
40
35

Table 7. Physical characteristics of the subjects including pre- and post-training means ± SE and % changes for the following measurements : age, height, weight, sum of 2 skinfolds, % body fat based on the Lohman equation.

TABLE 7. PHYSICAL CHARACTERISTICS OF SUBJECTS

	GROUPS					
	EXPERIMENTAL (n=13)			CONTROL (n=13)		
	PRE	POST	% Δ	PRE	POST	% Δ
AGE (yr)	10.5 ± 0.2	11.1 ± 0.2		10.8 ± 0.1	11.4 ± 0.1	
HEIGHT (cm)	140.1 ± 1.7	140.8 ± 1.7	0.53	141.0 ± 2.2	141.2 ± 2.0	0.59
WEIGHT (Kg)	36.5 ± 2.6	38.1 ± 2.7	4.47	35.4 ± 1.7	36.8 ± 1.8	3.87
$\sum$ 2 skfs[1]	22.9 ± 4.1	22.4 ± 4.3	−2.18	21.2 ± 2.9	20.8 ± 2.9	−1.89
BODY FAT %	17.9 ± 2.0	17.1 ± 2.6	−4.39	17.6 ± 1.8	16.9 ± 1.6	−3.93

[1]sum of triceps and subscapular skinfolds.
values are means ± SE * $p < 0.05$, ** $p < 0.01$.

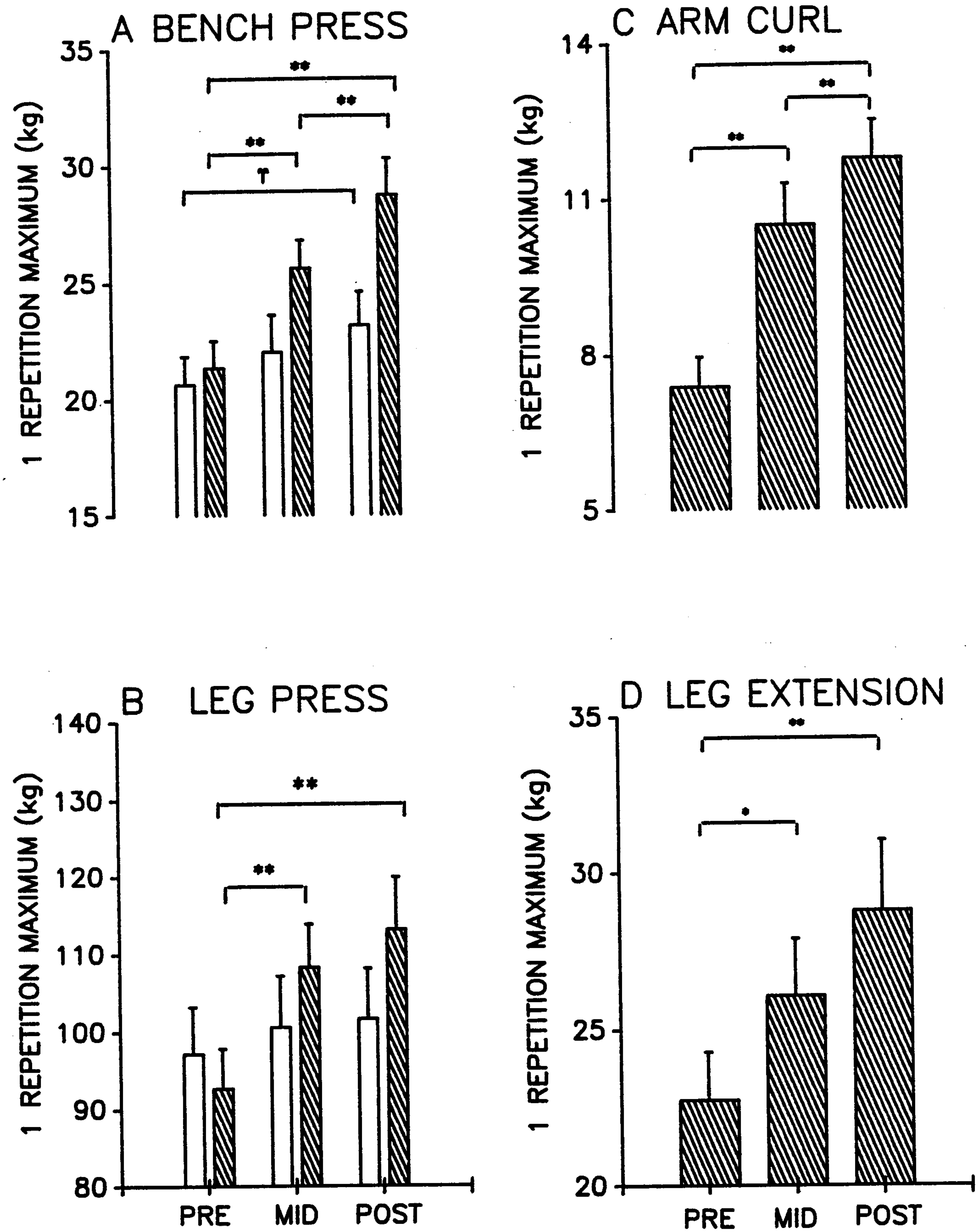
to scan the bone area, lean area of a specific muscle group (elbow flexor or knee extensor CSA) or total lean area, a significant difference in cross-sectional area was found. With a 1 centimeter difference between the two sites, a difference was found, only for the cross-sectional area of the elbow flexors and knee extensors, in 50 % of the cases.

B. Strength Performance Measurements

The performance strength measures for the one repetition maximum (1 RM) bench press (34.6 %, $p<.01$) and leg press (22.1 %, $p<.01$) increased with training (Figure 3A and B). For the bench press, the experimental group made significant gains in strength during phase 1 (20 %, $p<.01$) and phase 2 (14.6 %, $p<.01$) (Figure 3A). For the leg press, the significant increase in strength occurred only during the first training phase (16.8 %, $p<.01$) (Figure 3B). A significant increase in the 1 RM bench press (12.3 %, $p<.01$), indicative of growth, was also observed for the control group at the end of the study (Figure 3A). Both the bench press and the leg press strength measurements showed high day to day reliability (appendix A).

Significant increases were observed for the double arm curl after the first phase (42.2 %, $p<.01$) and the second phase (17.3 %, $p<.01$) of training in the experimental group (Figure 3C). Similar results were

Figure 3. Absolute changes in strength for the A) bench press, B) leg press, C) arm curl and D) leg extension strength performance measurements, pre-, mid- and post-training. Hatched and blank bars represent mean ± SE of experimental and control group, respectively. Training effect * $p<.05$, ** $p<.01$; growth effect τ $p<.05$.


A BENCH PRESS
1 REPETITION MAXIMUM (kg)
35
30
25
20
15
**
**
**
†
C ARM CURL
1 REPETITION MAXIMUM (kg)
14
11
8
5
**
**
**
B LEG PRESS
1 REPETITION MAXIMUM (kg)
140
130
120
110
100
90
80
**
**
PRE
MID
POST
D LEG EXTENSION
1 REPETITION MAXIMUM (kg)
35
30
25
20
**
*
PRE
MID
POST

observed for the double leg extension with increases of 14.7 % and 11.9 % after phase 1 and 2, respectively ($p<.05$ for pre-mid and mid-post and $p<.01$ for pre-post) (Figure 3D).

C. Muscular Endurance

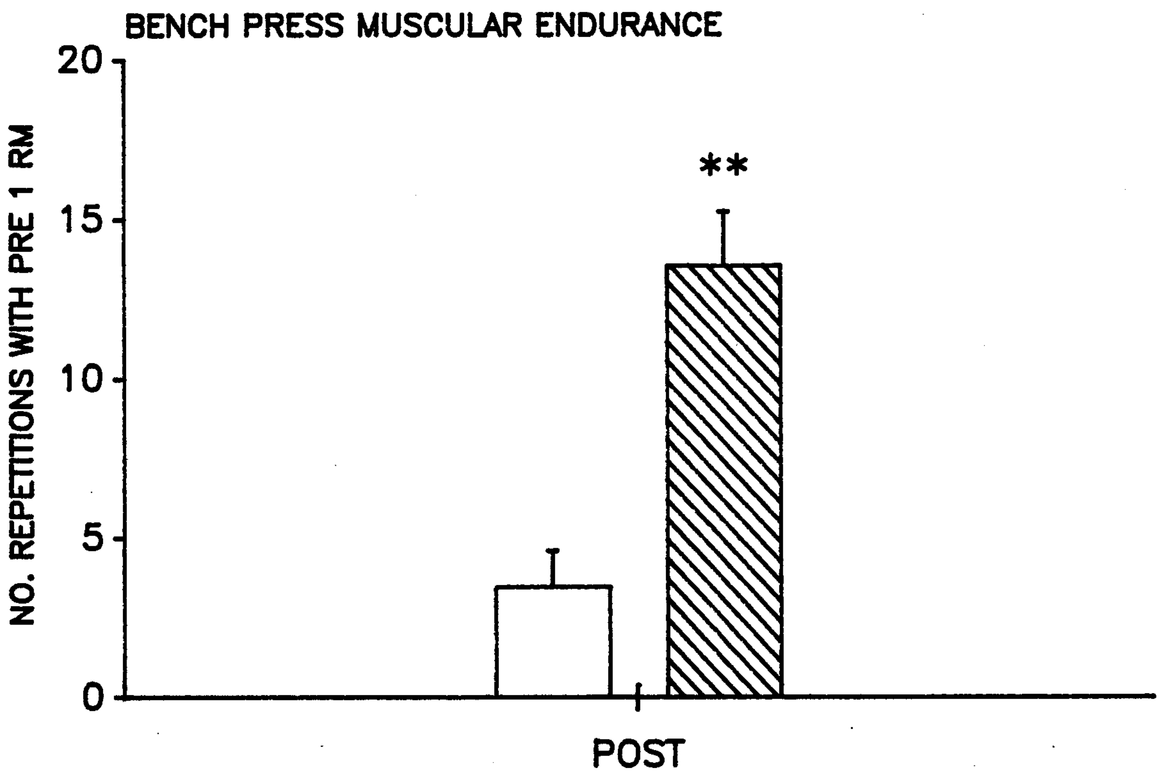
Muscular endurance in the bench press and leg press was significantly increased by training ($p<.01$) (Figure 4A and B). Significant differences between pre- and post-test measures were also observed for the double arm curl and double leg extension for the experimental group ($p<.01$) (Figure 4A and B).

D. Peak Isokinetic Torque

A significant training effect was observed for absolute isokinetic peak torque of the elbow flexor (+25.8 %, $p<.01$) and knee extensor (+21.3 %, $p<.01$) muscle groups (Figure 5A and B). For the elbow flexors a significant gain in peak torque was observed during the first (13.1 %, $p<.05$) and second (12.7 %, $p<.05$) 10 weeks of training. For the knee extensors a significant difference in peak torque was only observed during the first training phase (17 %, $p<.01$).

The day to day reliability (appendix A) for maximal voluntary isometric peak torque was lower than that of the 1 repetition maximum and maximal voluntary isometric peak

Figure 4. Muscular endurance performance measurements: absolute number of repetitions completed with pre-training 1 RM for the A) bench press and B) leg press. Hatched and blank bars represent mean ± SE of experimental and control groups. Training effect ** $p<.01$.


BENCH PRESS MUSCULAR ENDURANCE
NO. REPETITIONS WITH PRE 1 RM
20
15
10
5
0
**
POST

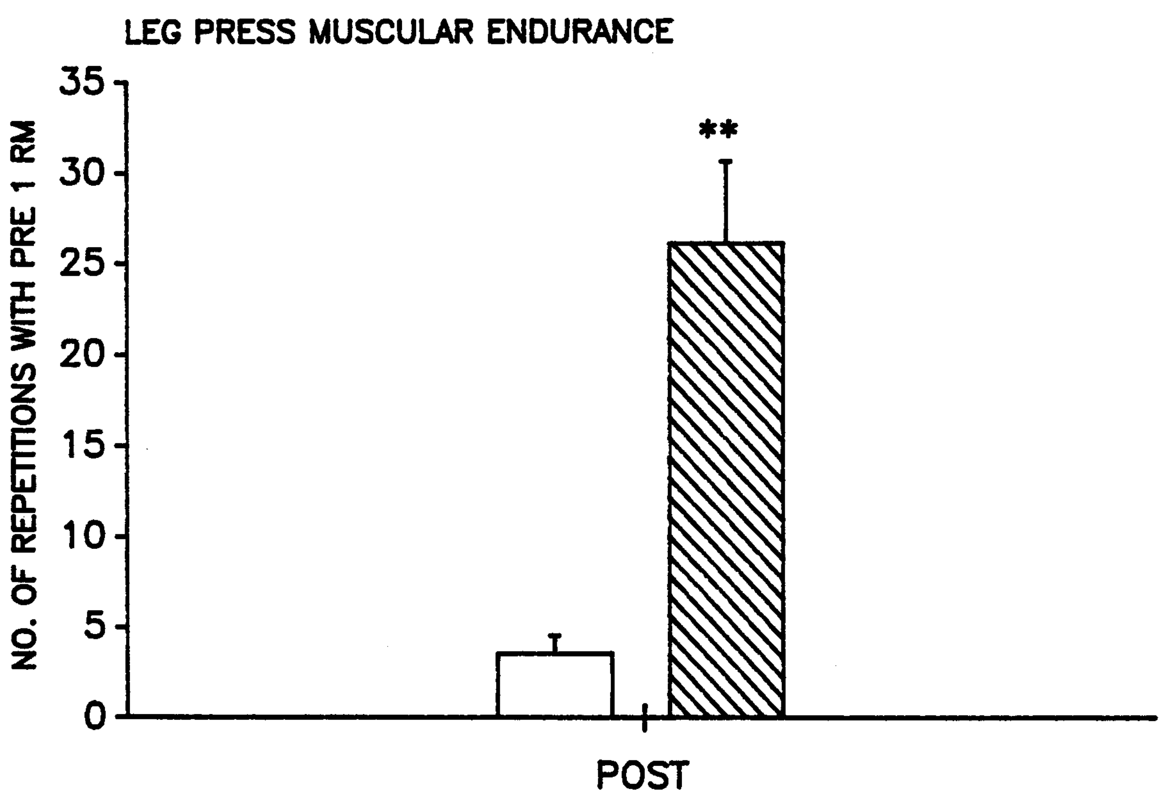
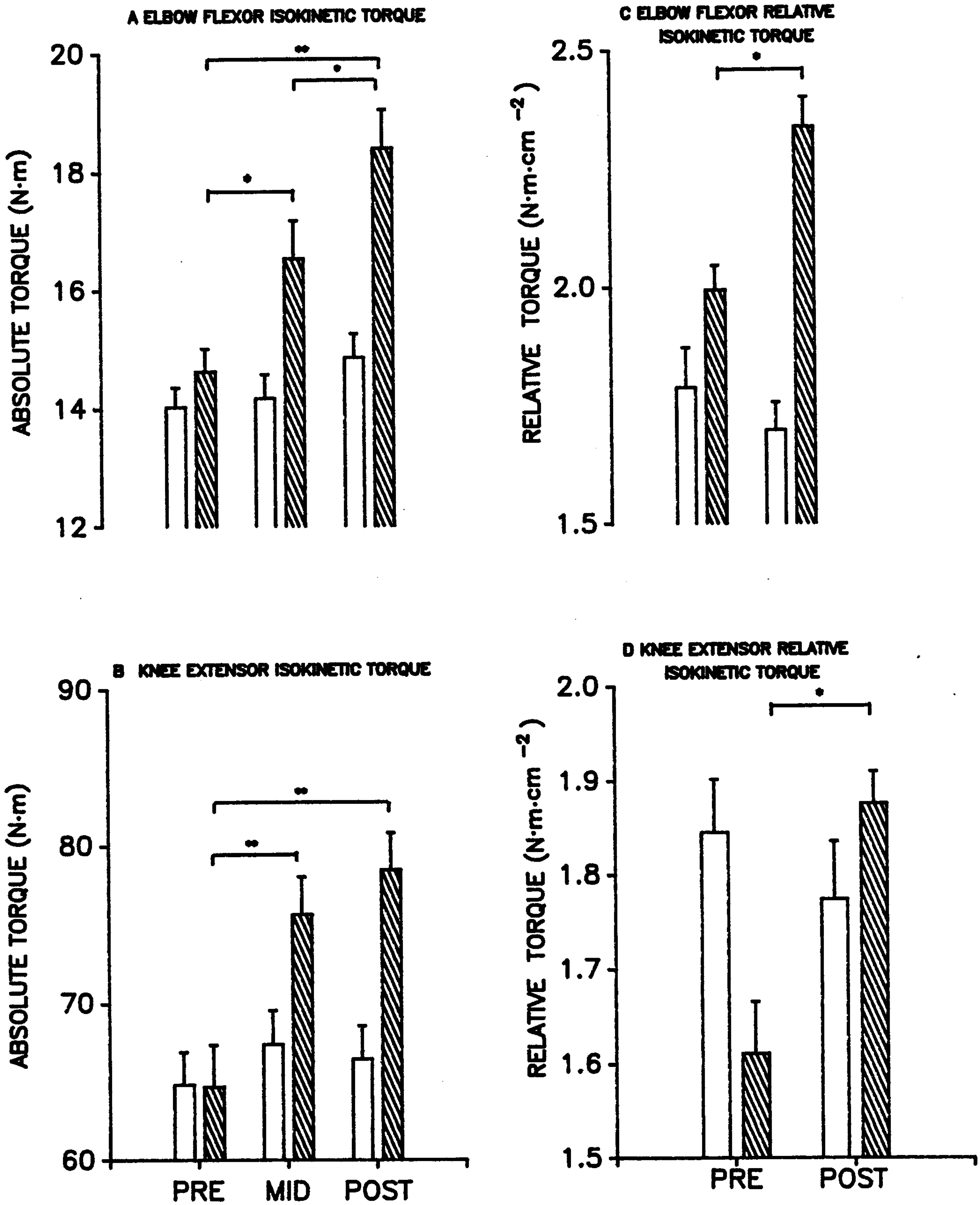

LEG PRESS MUSCULAR ENDURANCE
NO. OF REPETITIONS WITH PRE 1 RM
35
30
25
20
15
10
5
0
**
POST

Figure 5. Absolute and relative changes in maximal voluntary isokinetic peak torque measurements, pre-,mid- and post-training. Absolute changes : A) elbow flexion and B) knee extension, and relative changes : C) elbow flexion and D) knee extension (collapsed across velocities). Hatched and blank bars represent mean ± SE of experimental and control groups, respectively. Training effect * $p<.05$, ** $p<.01$; growth effect τ $p<.05$.


A ELBOW FLEXOR ISOKINETIC TORQUE
ABSOLUTE TORQUE (N·m)
20
18
16
14
12
C ELBOW FLEXOR RELATIVE ISOKINETIC TORQUE
RELATIVE TORQUE (N·m·cm −2)
2.5
2.0
1.5
B KNEE EXTENSOR ISOKINETIC TORQUE
ABSOLUTE TORQUE (N·m)
90
80
70
60
PRE
MID
POST
D KNEE EXTENSOR RELATIVE ISOKINETIC TORQUE
RELATIVE TORQUE (N·m·cm −2)
2.0
1.9
1.8
1.7
1.6
1.5
PRE
POST

torque measurements. The reliability was especially low for the elbow flexors at the highest velocity of contraction (3.14 rad·s^{-1}). Appendix A gives possible reasons for this lower reliability for the elbow flexors at 3.14 rad·s^{-1}. Trial to trial reliability ranged from high to very high.

A significant training effect was observed for elbow flexor (+17.2 %, $p<.05$) and knee extensor (+16.4 %, $p<.01$) peak torque normalized for muscle cross-sectional area (Figure 5C and D). Figure 6, presents the results separately for each velocity of contraction.

E. Peak Isometric Torque

A significant training effect was observed for absolute voluntary isometric peak torque of the elbow flexors (+37.3 %, $p<.01$) (Figure 7A). The significant increase in strength of the elbow flexors occurred during both phase 1 (23.3 %, $p<.01$) and phase 2 (14 %, $p<.01$). A growth effect was observed for the control group for the same dependent measure (+12.1 %, $p<.01$) between the mid and post testing. For the knee extensors, the absolute peak isometric torque was significant at joint angles of 90° (+25.3 %, $p<.05$) and 120° (+13.3 %, $p<.05$) only (Figure 7B). The significant increase in strength for the knee extensors occurred during both phases of training for the 90° joint angle and only during the first phase for the 120° joint angle. The day to day and trial to trial

Figure 6. Absolute maximal voluntary isokinetic peak torque measurements across velocities of contraction (0.52, 1.05, 2.09 and 3.14 $rad \cdot s^{-1}$), pre-, mid- and post-training for A) elbow flexion and B) knee extension. Closed and open circles represent mean ± SE of experimental and control groups, respectively. Training effect
* $p < .05$.

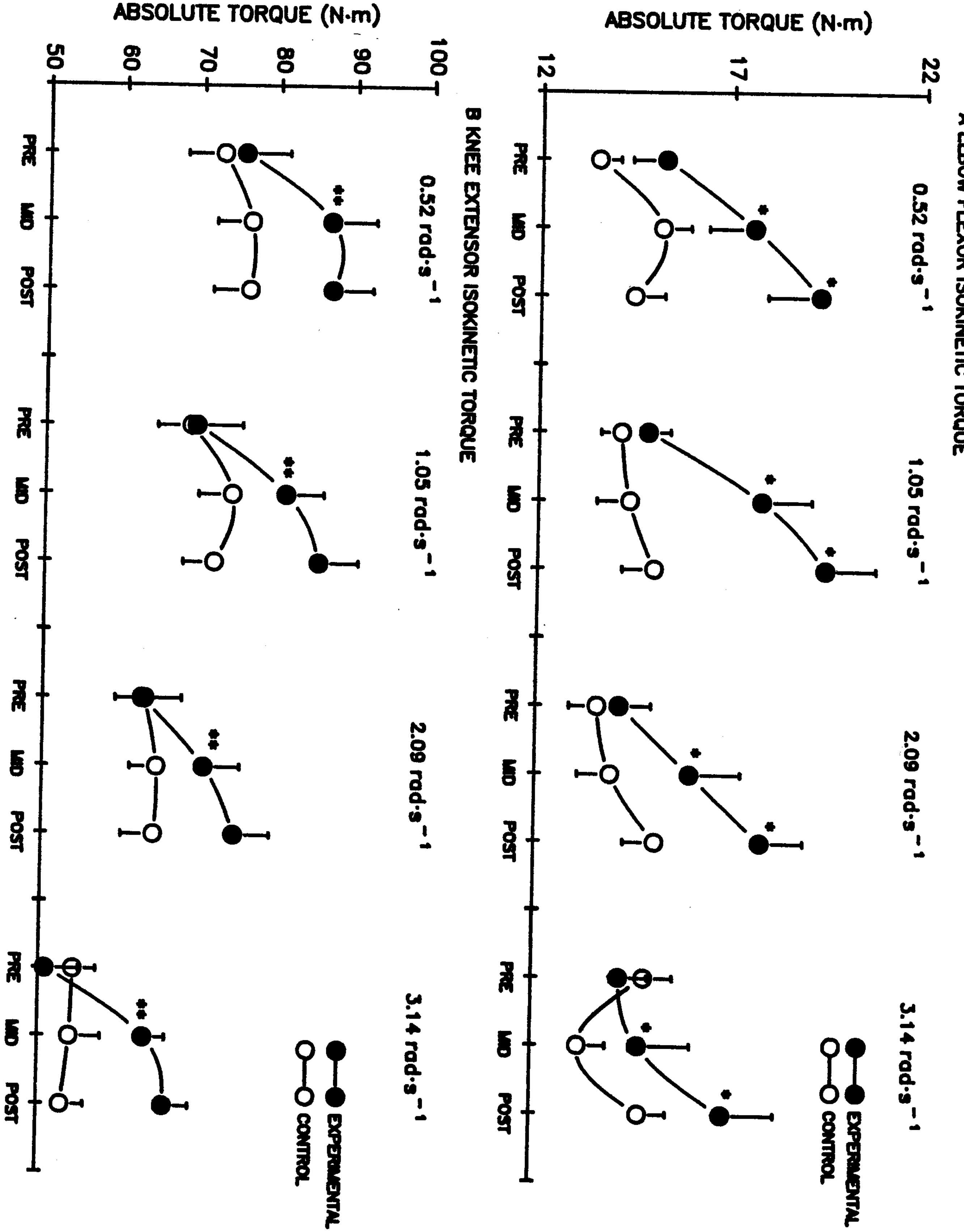

A ELBOW FLEXOR ISOKINETIC TORQUE
ABSOLUTE TORQUE (N·m)
12
17
22
0.52 rad·s⁻¹
1.05 rad·s⁻¹
2.09 rad·s⁻¹
3.14 rad·s⁻¹
PRE
MID
POST
EXPERIMENTAL
CONTROL
B KNEE EXTENSOR ISOKINETIC TORQUE
ABSOLUTE TORQUE (N·m)
50
60
70
80
90
100

Figure 7. Absolute changes in maximal voluntary isometric peak torque across joint angles of contraction pre-, mid- and post-training for A) elbow flexion (80°, 100°, 120° and 150°, full extension = 180°), and B) knee extension (90°, 120°, 140° and 160°, full extension = 180°). Closed and open circles represent mean ± SE of experimental and control group, respectively. Training effect ** $< .01$; growth effect ττ $p < .0$

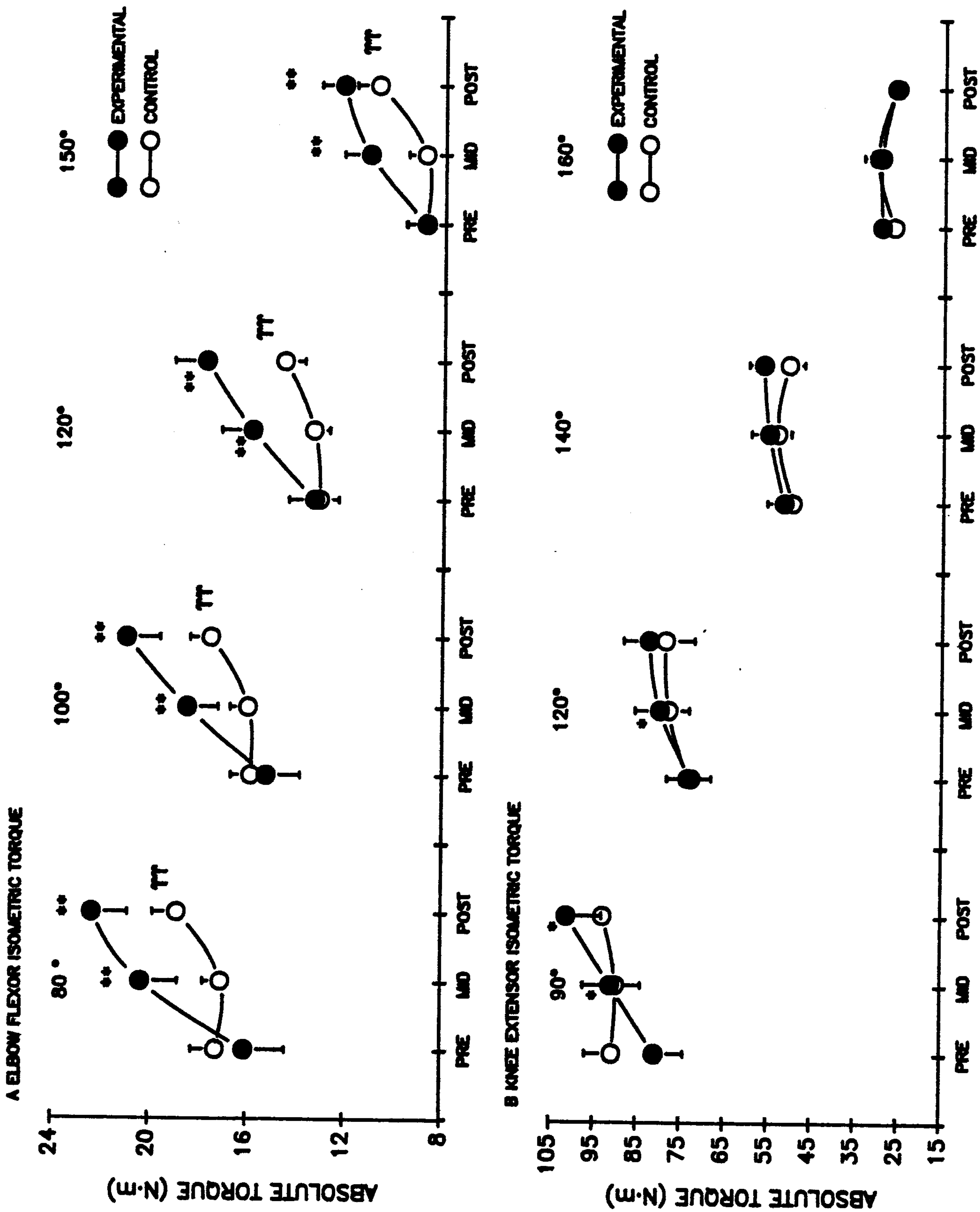
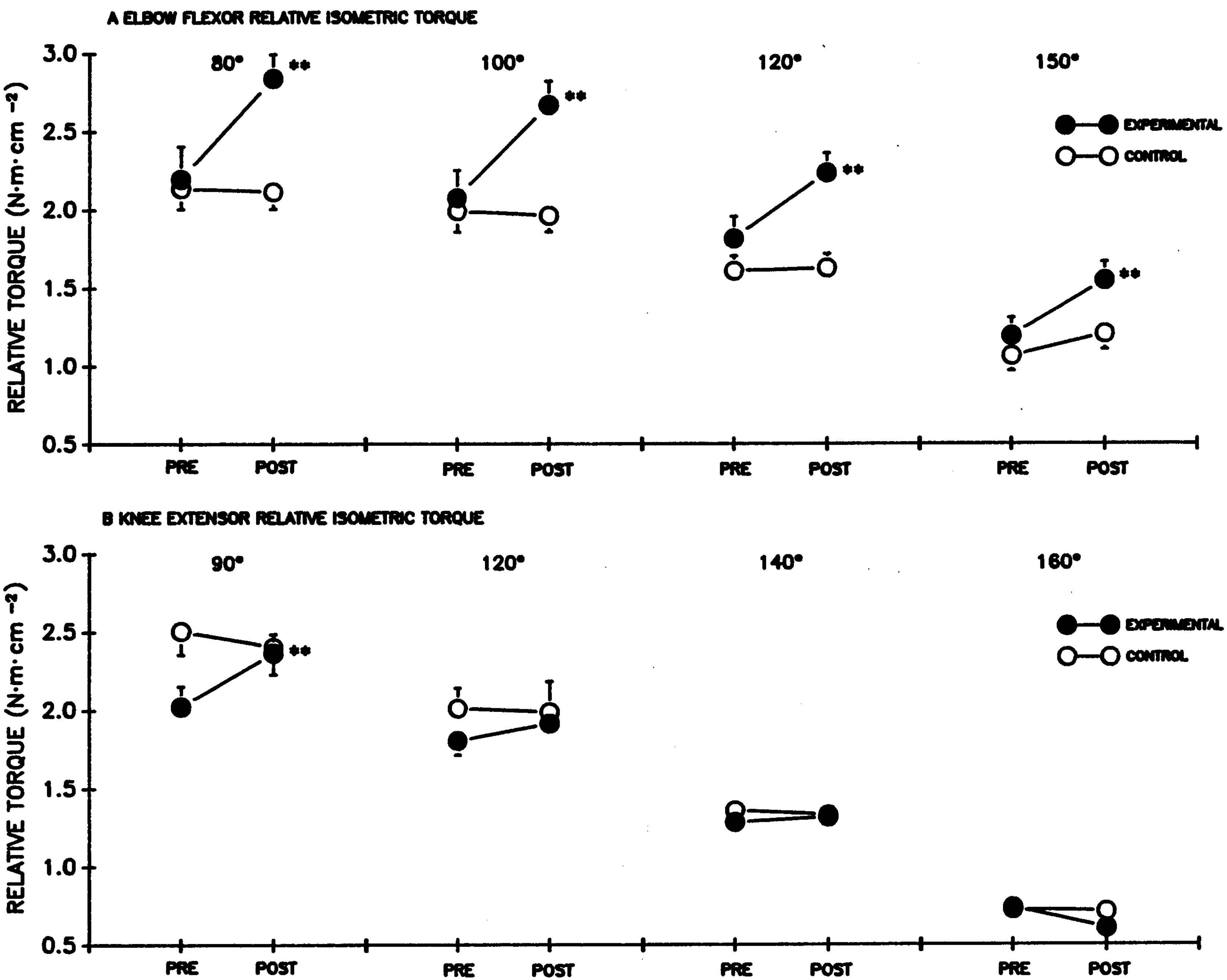

A ELBOW FLEXOR ISOMETRIC TORQUE
B KNEE EXTENSOR ISOMETRIC TORQUE
ABSOLUTE TORQUE (N·m)
EXPERIMENTAL
CONTROL
80°
100°
120°
150°
90°
120°
140°
160°
PRE
MID
POST
24
20
16
12
8
105
95
85
75
65
55
45
35
25
15

Figure 8. Relative normolized for muscle cross-sectional area maximal voluntary isometric peak torque measurements, across joint angles of contraction, pre-, mid- and post-training, for A) elbow flexion (80°,100°,120° and 150°, full extension = 180°) and B) knee extension (90°,120°,140° and 160°, full extension = 180°). Closed and open circles represent mean ± SE of experimental and control group, respectively. Training effect ** $p < .01$


A ELBOW FLEXOR RELATIVE ISOMETRIC TORQUE
RELATIVE TORQUE (N·m·cm ⁻²)
3.0
2.5
2.0
1.5
1.0
0.5
80°
100°
120°
150°
**
EXPERIMENTAL
CONTROL
PRE
POST
B KNEE EXTENSOR RELATIVE ISOMETRIC TORQUE
90°
120°
140°
160°

reliability (appendix A) for the maximal voluntary isometric peak torque ranged from high to very high.

There was a significant training effect on isometric peak torque of the elbow flexors normalized for muscle cross-sectional area $p<.01$) (Figure 8A). Growth had a significant effect at the 150° joint angle. For the knee extensors a training effect was observed only at the 90° joint angle (Figure 8B).

F. Isometrically Evoked Twitch Torque

There were significant training effects for absolute isometric evoked twitch torque of the elbow flexors (+29.6 %, $p<0.01$) and knee extensors (+29.7 %, $p<0.05$) (Figure 9A and B). The significant increases in isometric evoked twitch torque for both elbow flexors and knee extensors occurred during the last 10 weeks of training.

Training increased evoked twitch torque of the elbow flexors at all four joint angles used for testing (Figure 10A). Twitch torque for both the elbow flexors and the knee extensors exhibited high to very high day to day and trial to trial reliability (appendix A). Training had a significant effect on the isometric evoked twitch torque of the elbow flexors normalized for muscle cross-sectional area ($p<.01$), but not for the knee extensors (Figure 9C and D).

Figure 9. Absolute and relative changes in isometrically evoked twitch torque, pre-, mid- and post-training. Absolute changes : A) elbow flexion and B) knee extension, and relative changes : C) elbow flexion and D) knee extension (collapsed across joint angles). Hatched and blank bars represent mean ± SE of experimental and control groups, respectively. Training effect ** $p < .01$.

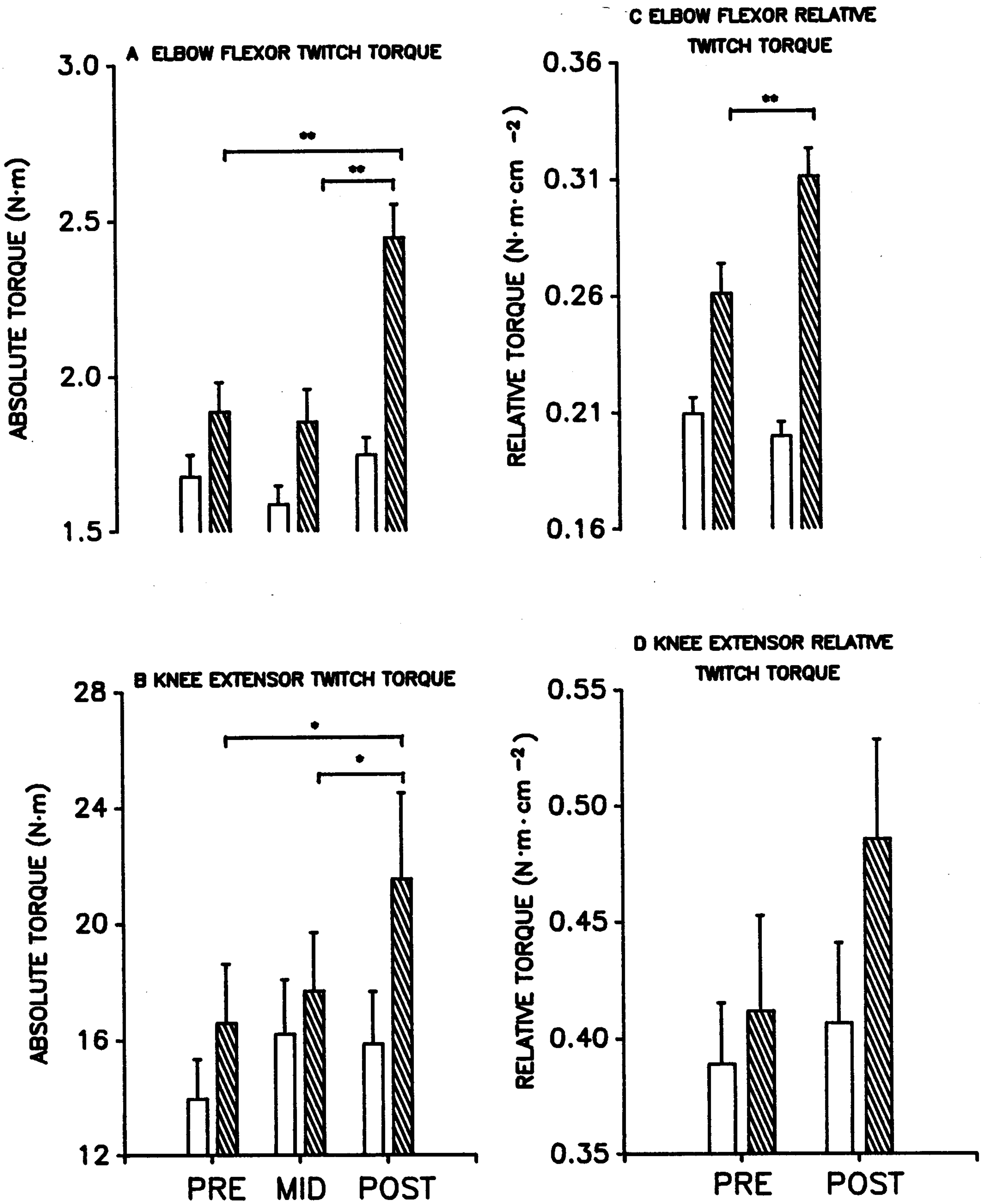
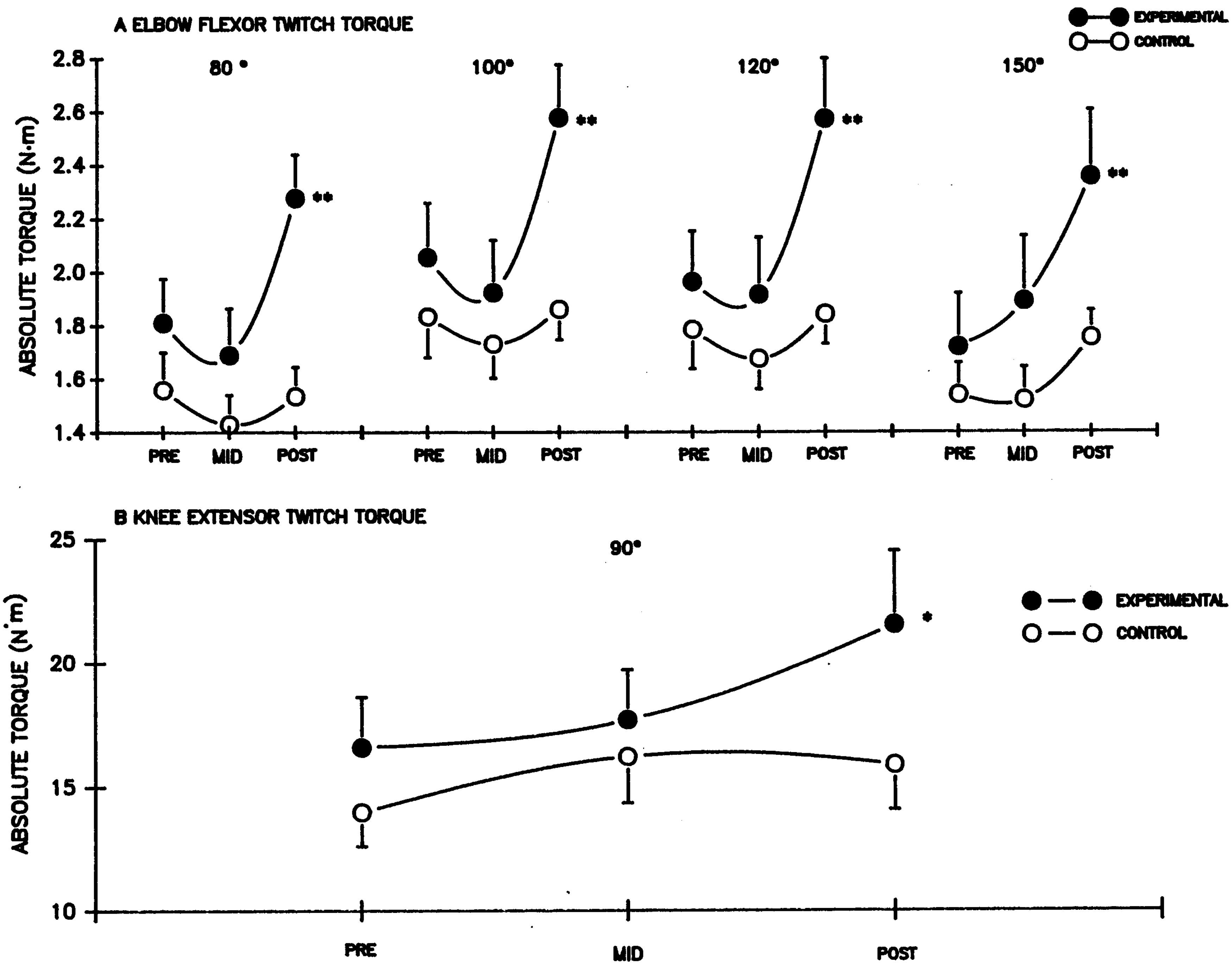

A ELBOW FLEXOR TWITCH TORQUE
ABSOLUTE TORQUE (N·m)
3.0
2.5
2.0
1.5
**
**
C ELBOW FLEXOR RELATIVE TWITCH TORQUE
RELATIVE TORQUE (N·m·cm −2)
0.36
0.31
0.26
0.21
0.16
**
B KNEE EXTENSOR TWITCH TORQUE
ABSOLUTE TORQUE (N·m)
28
24
20
16
12
*
*
PRE
MID
POST
D KNEE EXTENSOR RELATIVE TWITCH TORQUE
RELATIVE TORQUE (N·m·cm −2)
0.55
0.50
0.45
0.40
0.35
PRE
POST

Figure 10. Absolute isometrically evoked twitch torque, pre-, mid- and post-training, across joint angles, for A) elbow flexion (80°,100°,120° and 150°, full extension = 180°) and knee extension (90°, full extension = 180°). Closed and open circles represent mean ± SE of experimental and control group, respectively. Training effect * $p<.05$, ** $p<.01$


A ELBOW FLEXOR TWITCH TORQUE
EXPERIMENTAL
CONTROL
80 °
100°
120°
150°
ABSOLUTE TORQUE (N·m)
2.8
2.6
2.4
2.2
2.0
1.8
1.6
1.4
**
PRE
MID
POST
B KNEE EXTENSOR TWITCH TORQUE
90°
EXPERIMENTAL
CONTROL
*
ABSOLUTE TORQUE (N·m)
25
20
15
10
PRE
MID
POST

G. % Motor Unit Activation

Initial values for % motor unit activation (MUA) combining both experimental and control groups were 89 % and 78 % for elbow flexors and knee extensors, respectively. Neither training or growth had any significant effect on the % MUA of the elbow flexors or knee extensors (Figure 11A and B). However, there was a trend toward increased % MUA for both elbow flexors (13.2 %) and knee extensors (17.4 %) in the experimental group. There was no change in % MUA for elbow flexors during the study for the control group. In comparison, knee extensor % MUA showed a slight decrease at the end of the study, while the mid-point results indicated a 6.5 % increase over the initial value.

H. Time-related Contractile Properties

With the exception of the elbow flexor maximum rate of torque relaxation (MRTR) (+18.8 %, $p<.05$) (Figure 13 and 14), there was no differential effect of training for either elbow flexor or knee extensor time-related contractile properties. The training effect for elbow flexor MRTR was observed during the second training phase (+10.3 %, $p<.05$). A growth effect was observed, for the MRTD of the elbow flexors and knee extensors, during the second and first phase of training, respectively (+18.2 % ;

Figure 11. Percent motor unit activation, pre-, mid- and post-training, for A) elbow flexion (100°) and B) knee extension (90°). Hatched and blank bars represent mean of experimental and control groups, respectively.

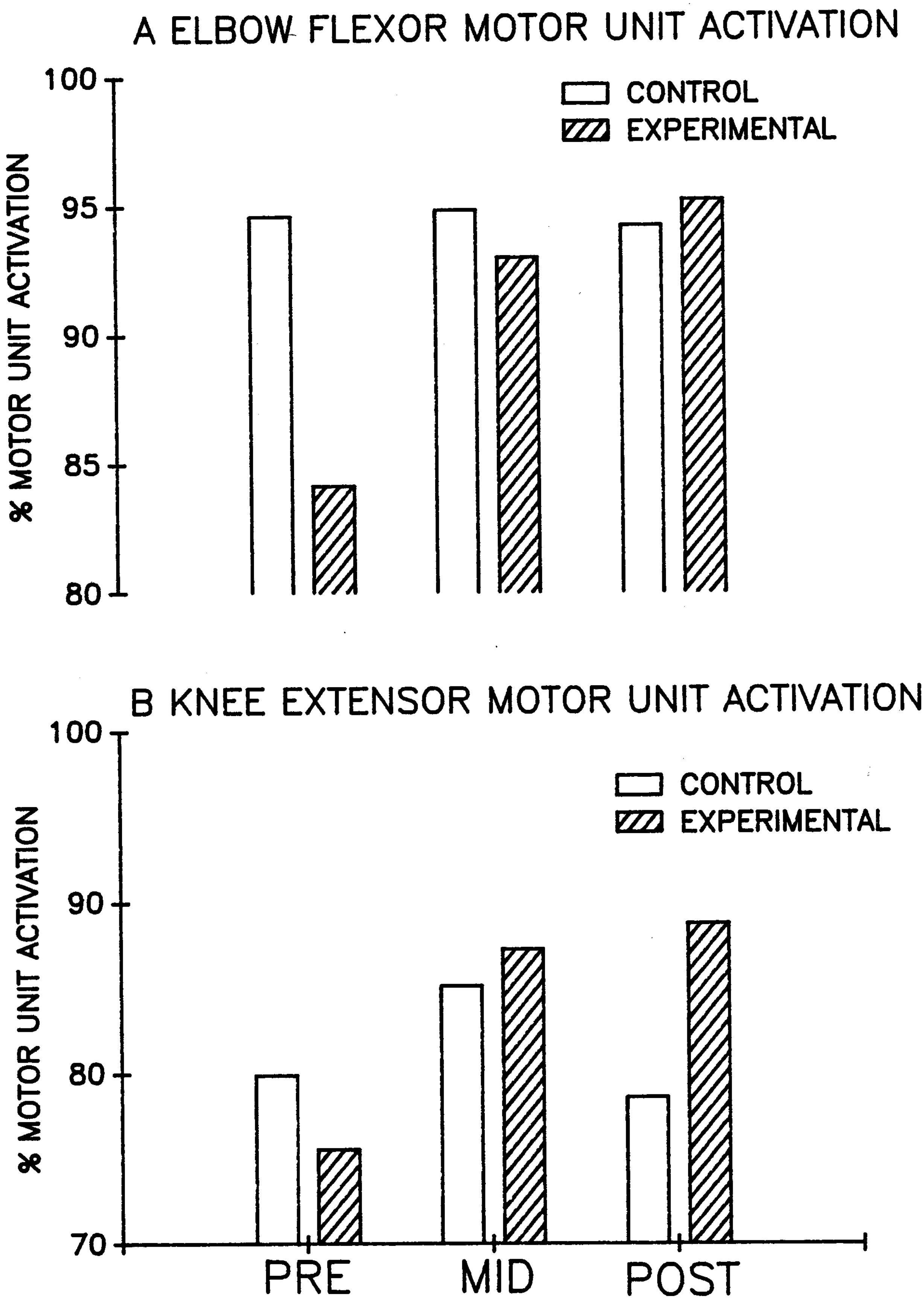

A ELBOW FLEXOR MOTOR UNIT ACTIVATION
% MOTOR UNIT ACTIVATION
100
95
90
85
80
CONTROL
EXPERIMENTAL
B KNEE EXTENSOR MOTOR UNIT ACTIVATION
% MOTOR UNIT ACTIVATION
100
90
80
70
CONTROL
EXPERIMENTAL
PRE
MID
POST

Figure 12. Time related contractile properties, pre-, mid- and post-training results for time to peak torque, half-relaxation time, total contraction time, maximum rate of torque development and maximum rate of torque relaxation for elbow flexion (collapsed across joint angles). Hatched and blank bars represent mean ± SE of experimental and control groups, respectively. Training effect * $p<.05$.

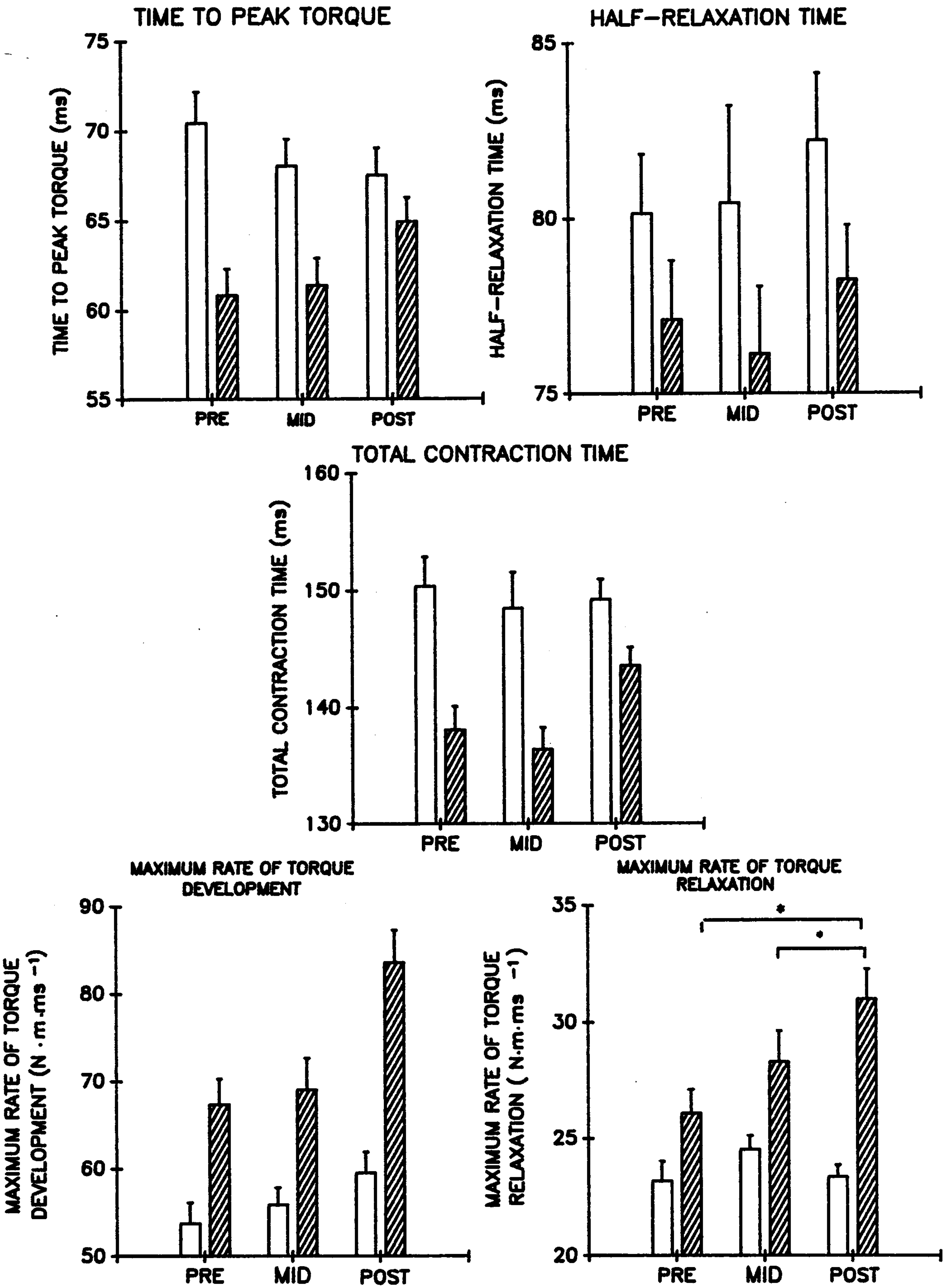
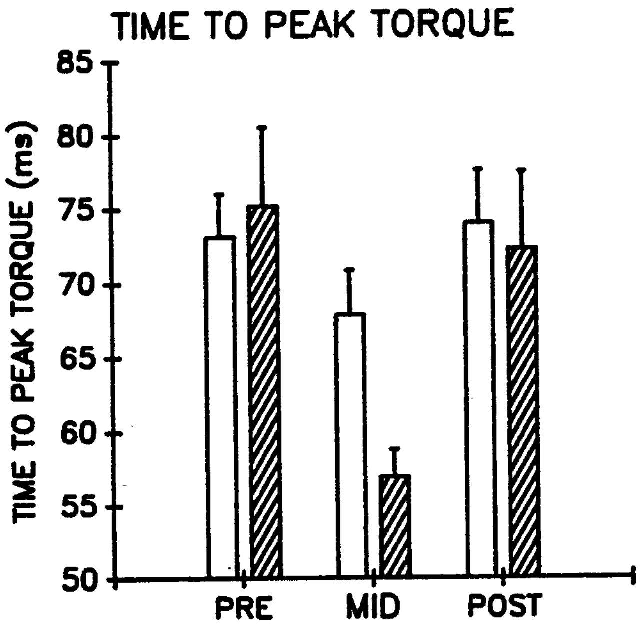
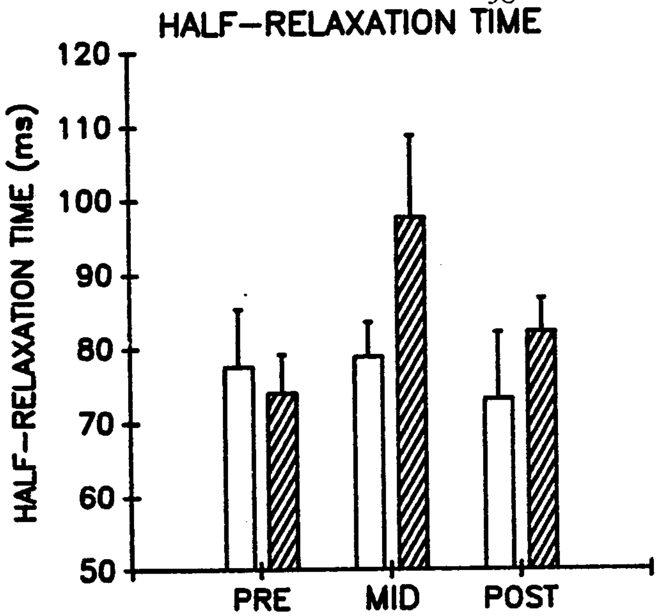
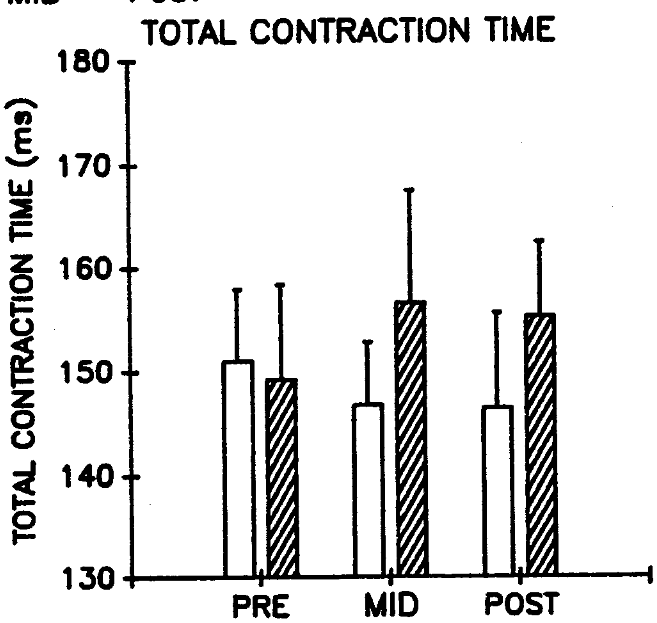
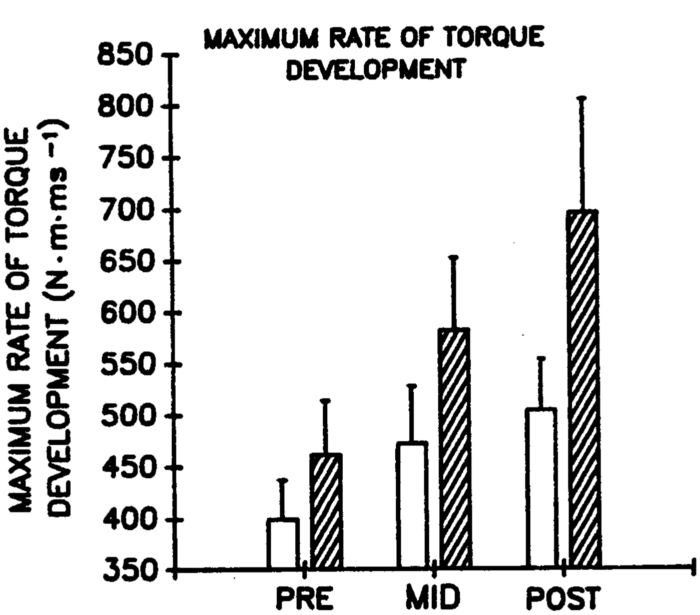

TIME TO PEAK TORQUE
TIME TO PEAK TORQUE (ms)
75
70
65
60
55
PRE
MID
POST
HALF-RELAXATION TIME
HALF-RELAXATION TIME (ms)
85
80
75
PRE
MID
POST
TOTAL CONTRACTION TIME
TOTAL CONTRACTION TIME (ms)
160
150
140
130
PRE
MID
POST
MAXIMUM RATE OF TORQUE DEVELOPMENT
MAXIMUM RATE OF TORQUE DEVELOPMENT (N·m·ms −1)
90
80
70
60
50
PRE
MID
POST
MAXIMUM RATE OF TORQUE RELAXATION
MAXIMUM RATE OF TORQUE RELAXATION (N·m·ms −1)
35
30
25
20
*
*
PRE
MID
POST

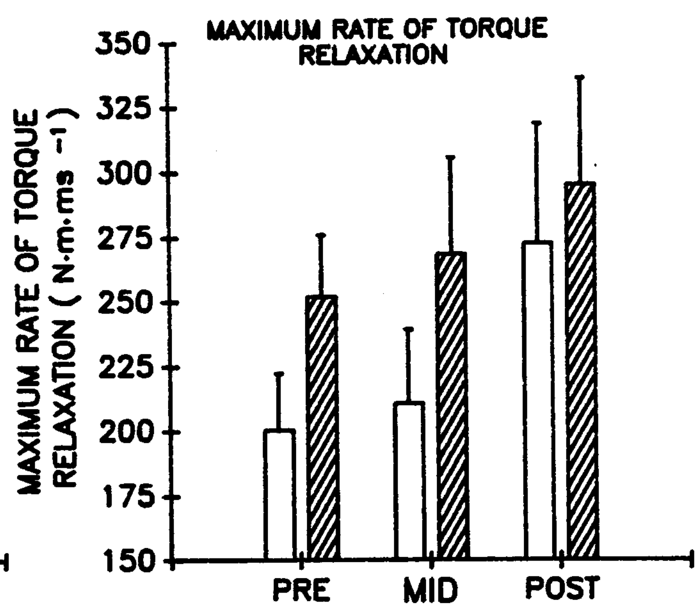
Figure 13. Time-related contractile properties, pre-, mid- and post-training results for time to peak torque, half-relaxation time, total contraction time, maximum rate of torque development and maximum rate of torque relaxation for knee extension. Hatched and blank bars represent mean ± SE of experimental and control groups, respectively.


TIME TO PEAK TORQUE
TIME TO PEAK TORQUE (ms)
85
80
75
70
65
60
55
50
PRE
MID
POST


HALF-RELAXATION TIME
HALF-RELAXATION TIME (ms)
120
110
100
90
80
70
60
50
PRE
MID
POST


TOTAL CONTRACTION TIME
TOTAL CONTRACTION TIME (ms)
180
170
160
150
140
130
PRE
MID
POST


MAXIMUM RATE OF TORQUE DEVELOPMENT
MAXIMUM RATE OF TORQUE DEVELOPMENT (N·m·ms −1)
850
800
750
700
650
600
550
500
450
400
350
PRE
MID
POST


MAXIMUM RATE OF TORQUE RELAXATION
MAXIMUM RATE OF TORQUE RELAXATION (N·m·ms −1)
350
325
300
275
250
225
200
175
150
PRE
MID
POST

+38.9 %, p<.01). A growth effect was also observed for TPT, of the knee extensors, during the first phase (-15.5 %, p<.01). TPT had increased back (16.9 %, p<.01), to approximately it's original value, by the end of the study.

Day to day reliability of time-related contractile properties (appendix A) varied depending on the limb, the contractile property examined and the statistical technique used to determine reliability. In general, higher reliability was found for the knee extensors than for the elbow flexors. Although, trial to trial reliability for the contractile properties was higher than the day to day reliability, wide fluctuations were again observed.

I. Ratio of isometric twitch torque to maximum voluntary isometric torque

Although the twitch torque to maximum isometric voluntary torque ratio of the elbow flexors was not significantly affected by training, a decreased of 31 % was observed during the first phase (Figure 14A). However, this decrease had disappeared by the end of the second phase, giving a post-test value similar to the pre-test value. No significant change was observed for this dependent variable for knee extensors (Figure 14B).

Figure 14. Ratio of twitch torque to maximum voluntary isometric torque, pre-, mid- and post-training, for A) elbow flexion and B) knee extension (collapsed across joint angles). Hatched and blank bars represent mean ± SE of experimental and control groups, respectively. Growth effect τ $p < .05$.

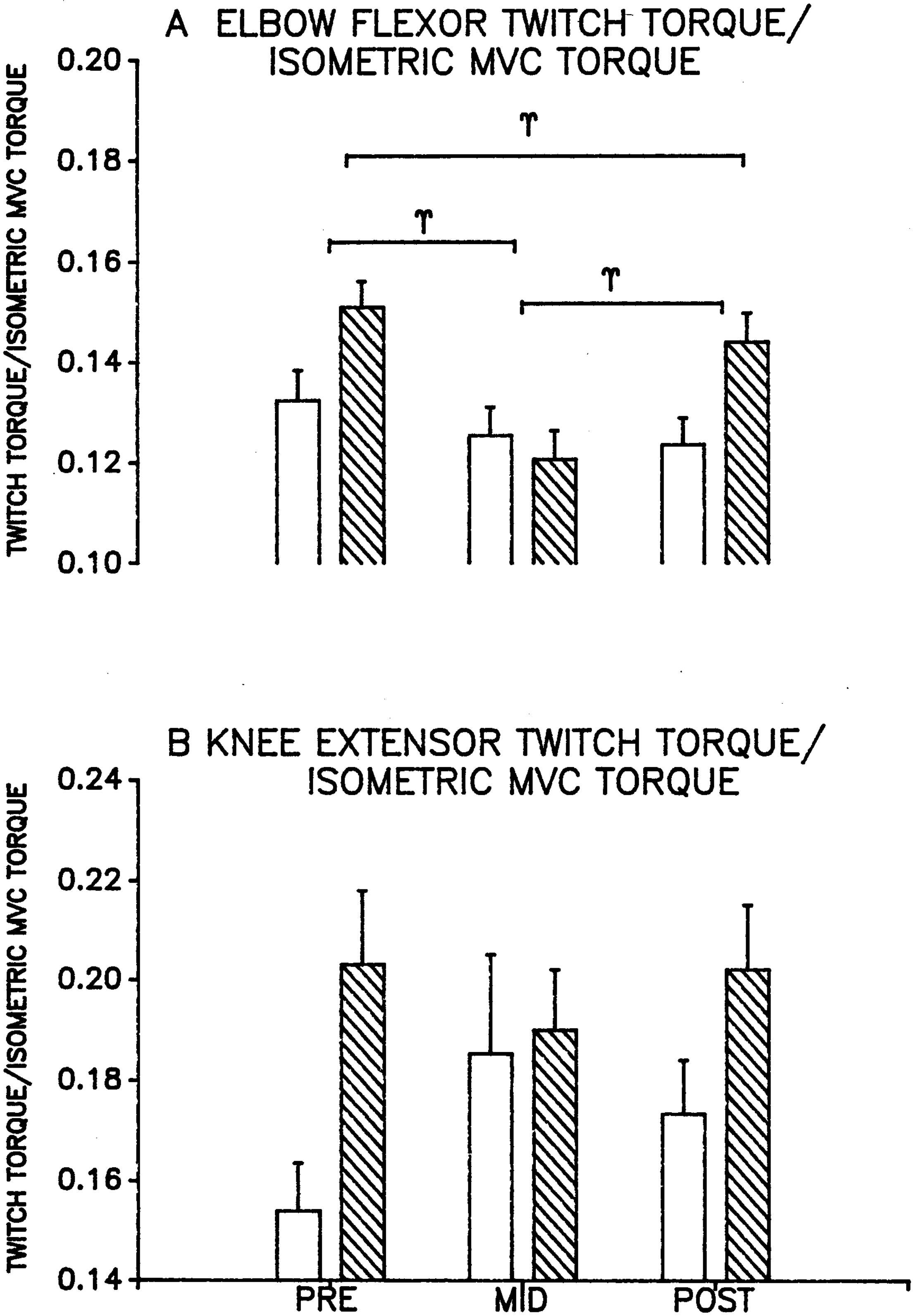

A ELBOW FLEXOR TWITCH TORQUE/
ISOMETRIC MVC TORQUE
TWITCH TORQUE/ISOMETRIC MVC TORQUE
0.20
0.18
0.16
0.14
0.12
0.10
B KNEE EXTENSOR TWITCH TORQUE/
ISOMETRIC MVC TORQUE
TWITCH TORQUE/ISOMETRIC MVC TORQUE
0.24
0.22
0.20
0.18
0.16
0.14
PRE
MID
POST

Table 8. Summary table : effect of training on the dependent variables

		Level of significance		% change	
		Mid	Post	Mid	Post
1) One repetition maximum :	bench press	p<.01	p<.01	20.0	34.6
	leg press	p<.01	p<.01	16.8	22.1
2) Muscular endurance :	bench press		p<.01		-
	leg press		p<.01		-
3) Isokinetic strength :	elbow flexors	p<.05	p<.01	13.1	25.8
	knee extensors	p<.01	p<.01	17.0	21.3
4) Isometric strength :	elbow flexors	p<.01	p<.01	23.3	37.3
	knee extensors				
	90°	p<.05	p<.05	12.6	25.3
	120°	p<.05	p<.05	9.9	13.3
B) Evoked contractile properties					
Twitch torque :	elbow flexors	NS	p<.01	-	29.6
	knee extensors	NS	p<.05	-	29.7
Time to peak torque :	elbow flexors	NS	NS	-	-
	knee extensors	NS	NS	-	-
Half-relaxation time :	elbow flexors	NS	NS	-	-
	knee extensors	NS	NS	-	-
Total contraction time :	elbow flexors	NS	NS	-	-
	knee extensors	NS	NS	-	-

		Level of significance		% change	
		Mid	Post	Mid	Post
Maximum rate of torque development :	elbow flexors	NS	NS	-	-
	knee extensors	NS	NS	-	-
Maximum rate of torque relaxation :	elbow flexors	NS	p<.05	-	18.8
	knee extensors	NS	NS	-	-
C) Interpolated twitch					
% motor unit activation :	elbow flexors	NS	NS	-	-
	knee extensors	NS	NS	-	-
D) Muscle cross-sectional area					
	elbow flexors	-	NS	-	-
	knee extensors	-	NS	-	-
E) Anthropometry					
Girth :	arm	NS	p<.05	-	3.9
	thigh	NS	NS	-	-

Chapter V

Discussion

The present investigation differed from previous studies exploring the effect of resistance training in the prepubescent population in several respects. First, this study lasted 6 weeks longer than the longest study to date (Weltman et al., 1986) and was twice the length of typical studies examining this question. This was important since it gave enough time for all possible adaptations influencing strength to manifest themselves. Second, by including mid-testing, the study offered a way to monitor the time course of some of these adaptations. Third, different modes of testing were used to evaluate the specific (one repetition maximum on the weight training station) and non-specific (isometric and isokinetic muscle action) adaptations in strength, eliminating any bias in the measurement of the strength gains.

This was also the first investigation to attempt to differentiate the neurologic and morphological mechanism(s) underlying increases in strength, with resistance training, in prepubescent boys. Computerized axial tomography (CAT) was used for accurate measurement of cross-sectional area (CSA). To assess the possible role of neural adaptations, the degree of motor unit activaton was measured using the twitch interpolation technique. Twitch torque and time related evoked contractile properties were also measured to determine other possible adaptations at the muscle level.

A. Anthropometric and Cross-sectional Characteristics

While the inclusion of a control group was not a distinctive feature of this study, it was essential to differentiate between the effect of training and growth on the dependent variables. Care was taken to match boys of similar age and level of puberty. The similar pre-training values for age, height, weight, sum of skinfolds and % body fat for both the experimental and control groups indicates that the groups were fairly well matched.

Cross-sectional areas of the trained muscle, as measured by CAT, were not affected by training. While the validity and reliability of the technique for measuring single muscle bellies is questionable (see appendix B), the lack of increase in total lean arm and leg CSA, suggest that muscle hypertrophy was not an important factor contributing to the strength increases observed in this study.

B. Voluntary strength

The results of this study indicated that 20 weeks of traditional circuit weight training, incorporating progressive resistive loading and both concentric and eccentric muscle actions, significantly improved performance strength for the 1 repetition maximum (1 RM) bench press and leg press in prepubescent boys. While there was no comparable data for the control group for these particurlar exercises, there were also significant increases in double arm curl and leg extension strength, suggesting a training effect. Results for the 1RM performance strength measures in the present study appear to agree with McGovern's (1984) findings of increased strength in the bench press and arm curl for 4th, 5th and 6th graders following 12 weeks of circuit weight training. Details regarding the specifics of the training program and the nature of the criterion strength measures were, however, not reported in McGovern's (1984) study.

Percent increases in bench press (35 %) and leg press (22 %) were comparable to results obtained with adults (Berger, 1963; Dons et al., 1979; Sailors & Berg, 1987) and pubescent children (Sailors & Berg, 1987). The absolute increase in bench press strength (7.4 kg) in the prepubescent children was also comparable to increases in the same lift for adults (10.3 kg) and pubescent children (5.2 kg) (Sailor and Berg, 1987).

Although the duration of training in the present study was more than twice that in these adult studies, significant increases in strength (bench press (20 %) and

leg press (17 %) were evident in the present study even after 10 weeks of training. Although the direction of change was similar to that observed in adult studies, the magnitude, both in absolute and relative terms, of the strength gains, was somewhat smaller. The significant increase in maximal voluntary isometric peak
torque for elbow flexion observed in the present study conflicts with Vrijens' (1978) earlier finding of no significant effect of 8 weeks of weight training on isometric strength of the elbow flexors (EF) in prepubescent males. The discrepancy in results between studies may be explained by differences in the length of the training programs, and more importantly by the higher training load and volume used in the present study.

The percent increase in isometric torque of the EF (37 %) was similar to that observed in adults (36 %) (Moritani and deVries, 1979). After 10 weeks of training, a duration comparable to that used by Moritani and deVries (1979), an increase of only 23 % was observed. The % increase in knee extensor (KE) isometric torque at 90° was higher than the increases reported in adult studies of a shorter duration (Thorstensson et al., 1976a; Thorstensson et al., 1976b). Results from short (Thorstensson et al., 1976a; Thorstensson et al., 1976b; Dons et al., 1979) and long duration (Hakkinen and Komi, 1983; Hakkinen and Komi, 1985) adult studies, using the squat exercise suggest that smaller gains in isometric strength are observed with this muscle group and mode of testing. This point will be addressed in more detail later in the discussion.

The improvement in isokinetic peak torque for the EF (26 %) and KE (21 %) agrees with the finding of Pfeiffer and Francis (1986) and Weltman et al. (1986). The Pfeiffer and Francis (1986) study should be interpreted carefully, because of the lack of statistical comparison between the experimental and control groups, variation in training response between contralateral limbs, and the decrease in limb strength at some velocities of contraction for particular groups of subjects. Despite these problems, the study reported large increases in isokinetic torque in some of the trained muscle groups. EF torque increased in the order of 15 and 23 % at 0.524 and 2.094 $rad \cdot s^{-1}$, respectively and KE torque at 2.094 $rad \cdot s^{-1}$ increased by about 18 %. In the present study, increases in isokinetic torque for elbow flexion at the same velocities of contraction were 26.5 and 26.1 %, respectively, and for knee extension at 2.094 $rad \cdot s^{-1}$, it was 19 %. Curiously, for knee extension at 0.524 $rad \cdot s^{-1}$, Pfeiffer et al. (1986) obtained an increase of only 6.5 %, in contrast to the 15 % increase observed in the present study.

Weltman et al. (1986) observed increases in average isokinetic elbow flexion peak torque (mean of torque outputs across 9 ranges of motion) of approximately 29 %

and 35 % at 0.524 and 1.571 $rad \cdot s^{-1}$, respectively. For knee extension, at the same velocities of contraction, they observed average increases in torque of 23 % and 19 %. The slightly higher increases in torque in this study compared to the present investigation can be explained by differences in the mode of training (hydraulic resistance) used. Although hydraulic resistance devices do not provide "true" isokinetic resistance (O'Hagan, 1987), they should favour greater increases in isokinetic torque than weight training, when testing is done on a Cybex dynamometer, because of specificity of the contraction type.

The percent increase in isokinetic strength of EF and KE in the present study agrees with results for the elbow extensor of adults (MacDougall et al., 1977). MacDougall et al. (1977) used a weight training program which lasted 20 weeks, and which resulted in a 28 % increase in elbow extensor torque.

The data in Appendix A on day to day and trial to trial reliability show that children can be evaluated, with confidence, for maximal voluntary strength measurements.

C. Evoked contractile properties

To the author's knowledge, there are no published reports on the effect of resistance training on the evoked contractile properties of prepubescent children. In the present investigation, an increase of approximately 30 % in the twitch torque of both elbow flexors and knee extensors was observed at the end of the training period. In adults, only Liberson and Asa (1959) have reported an increase in twitch tension of the hypothenar muscles, in some of their subjects after weight training. More recently, Duchateau and Hainaut (1984) found a decrease (-9 %) in twitch tension for the adductor pollicis after dynamic training and an increase (20 %) after isometric training. The discrepancy between the results of these two studies may well be related to differences in training intensity. Liberson and Asa (1959) used 3 sets of 10 repetitions at 50, 75 and 100 % of the 10 RM. The load was increased each week according to the method of progressive resistance developed by DeLorme (1948). In contrast, Duchateau and Hainaut (1984) used a high volume of training, 10 sets of 10 repetitions, but the load was only 30 to 40 % of the maximum isometric force. The lower load was chosen to allow fast dynamic contraction, a situation that may have resulted in sub-maximal activation of the trained muscle. However, Sale et al. (1982a and 1983a), despite subjecting various muscles to high intensity isometric and weight training, obtained decreases in twitch tension.

The electrically evoked twitch contraction is a measure of the intrinsic force-producing capacity of muscle (McDonagh et al., 1983) and it is believed to be related to the muscle cross-sectional area (Close, 1972). Thus an increase in twitch torque should be supported by some change in muscle CSA. In the present investigation, changes in elbow flexion and knee extension twitch torque were not accompanied by changes in CSA of the upper-arm and thigh, respectively.

These results could suggest that the torque per unit of cross-sectional area (specific tension) increased with training. If this was the case, part of the gain in voluntary strength could be attributed to the increase in specific tension. However, it is difficult to make a definite statement on muscle maximal force or specific tension without measuring tetanic torque. A single twitch does not induce maximal activation of a muscle (Close, 1972), so that changes in twitch torque do not necessarily reflect changes in maximal force capacity of the muscle.

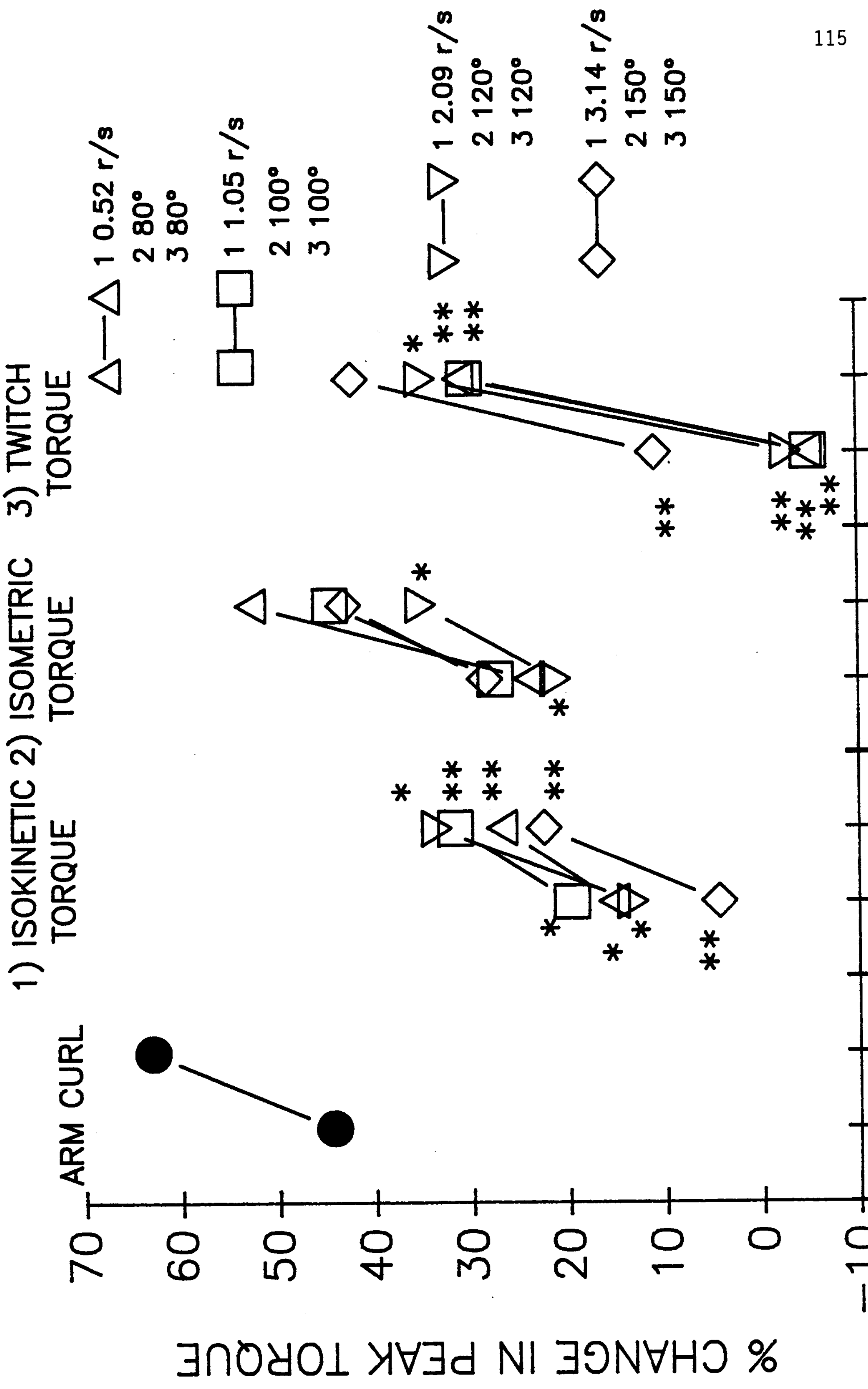
The increase in twitch torque could also be explained by an increase in the density of myofibrils, not reflected in the CSA of muscle. However, two training studies conducted with adult subjects, involing weight training have reported no alterations in the myofibrillar volume density (MacDougall et al., 1979; Luthi et al., 1986). The spacing of the myosin filaments was found to be consistent within a subject both centrally and peripherally in the myofibril (MacDougall et al., 1979). Since this spacing is constant, any increase in contractile elements due to resistance training must be added on the periphery of the myofibril (MacDougall, 1986). Variations in volume-density of myofibrils in prepubescents, because of developmental growth, could possibly modify the influence of training on this muscle fibre component. However, this seems unlikely since the volume density of myofibrils in six year old children (Bell et al., 1980) was found to be similar to that of adults (MacDougall et al., 1979).

The higher post-training twitch torque without changes in CSA, could also be the result of an increase in the fast twitch (FT)/slow twitch (ST) fibre area ratio and/or a change in the proportion of fast to slow twitch fibres independent of gross muscle hypertrophy. One argument, against this possibility, is the fact that there is apparently no correlation between muscle fiber composition and strength per unit of CSA (Schantz et al., 1983; Maughan and Nimmo, 1984a; Sale et al., 1987). Furthermore, in the present investigation, this possibility is, at best, speculative since muscle fibre type distribution and area can only be determined by the use of the muscle biopsy technique. However, because fast twitch fibers are capable of greater force development at higher velocities of contraction, an increase FT/ST area ratio or a change in the proportion of FT to ST fibres may be reflected in relative differences in the % change (% pre-test) with training at low and high velocities of contraction (Vandervoort et al., 1984). However, caution has been suggested when relating the force-velocity relationships to muscle morphology, because of possible neural inhibition at low velocities of contraction (Sale, 1983b). Training may reduce this inhibition (Sale, 1983b), so that the ratio of high to low velocity torque output could be smaller post- than pre-training.

The highest velocity of contraction used for these experiments was 3.14 $rad \cdot sec^{-1}$, a value that is far from the maximal velocity attainable by a limb during an unresisted movement (Sale and Norman, 1982). Given that no difference was found for the % change in torque among the four velocities of contraction (0.52, 1.04, 2.09 and 3.14 $rad \cdot sec^{-1}$) for the EF (Figure 15), these results suggests that training had no differential effect on the FT/ST fibre area ratio or fibre type distribution. In addition, a variation in fibre composition would have been reflected by changes in time to peak torque and/or half-relaxation time of the muscle, which were not observed in the present study.

Sale et al. (1982a) suggested that the decrease in twitch tension, observed in their study, was the result of a decrease in muscle stiffness. A single stimulus provides a contraction time that is too short to allow the series elastic elements to be "taken up". In contrast, greater muscle extensibility would hardly affect a maximum voluntary contraction (MVC) since the repeated stimulation

Figure 15. Comparison for the % change in peak torque at mid- and post-training, between the double arm curl on the training device and, the right elbow flexor isokinetic and isometric peak torque and evoked twitch torque. * p <.05, ** <.01.


% CHANGE IN PEAK TORQUE
70
60
50
40
30
20
10
0
−10
ARM CURL
1) ISOKINETIC TORQUE
2) ISOMETRIC TORQUE
3) TWITCH TORQUE
MID POST
MID POST
MID POST
MID POST
1 0.52 r/s
2 80°
3 80°
1 1.05 r/s
2 100°
3 100°
1 2.09 r/s
2 120°
3 120°
1 3.14 r/s
2 150°
3 150°

provides continuous tension on the series elastic elements.

The change in twitch torque, could involve more than passive mechanical properties of the muscle. It could be related to some chronic potentiation resulting from training adaptations of the excitation contraction coupling processes (Duchateau & Hainaut, 1984). Adaptations in the suggested mechanisms underlying acute twitch potentiation following a MVC could be partly responsible for the training associated increase in twitch torque. An increased release of Ca^{2+} from the terminal cisternae of the sarcoplasmic reticulum (SR) (Blinks et al., 1978) and an increased phosphorylation of the myosin light chain (Moore and Stull, 1984; Houston et al.,1985) which would increase the sensitivity of Ca^{2+} binding sites on troponin to Ca^{2+}, have been retained as possible factors playing a role in twitch potentiation.

In the present investigation, although training had no significant effect on the twitch torque to maximum voluntary isometric torque ratio of either the elbow flexors or knee extensors, a trend was observed for the elbow flexors. An increase of 23 % in the isometric MVC torque, with little change in twitch torque, was responsible for a 31 % decrease in the twitch to maximum voluntary isometric torque ratio of the EF, during the first phase of training. During the second phase, twitch torque increased substantially more (30 %) than the isometric MVC torque causing the ratio to increase (+19 %) and return to a value similar to the pre-training value.

An increase in muscle stiffness during the second phase of training could explain the increase in twitch torque and the recovery of the twitch torque to isometric MVC torque ratio to pre-test level. However, such a conclusion may be erroneous, since other factors (e.g. neural adaptations) not reflecting changes in the intrinsic characteristics of the muscle, may have influenced the isometric MVC response and indirectly the twitch torque to isometric MVC torque ratio. Therefore, the interpretation of this ratio to characterize changes in muscle stiffness with training, as opposed to the twitch torque to tetanic torque ratio, must be viewed cautiously, given the methodology used in this study.

Regarding the excitation-contraction coupling processes, it is also difficult to make any definite conclusions without any direct measurements of calcium movement (Ca^{2+} sensitive electrodes and Ca^{2+} indicators, for review see Klug & Tibbits, 1988). The increased twitch torque to MVC torque ratio, during the second phase, could be partly attributed to a greater release of Ca^{2+} from the SR, causing a higher saturation of the contractile protein. This increased Ca^{2+} release would only have a minimal effect on MVC torque, since during the high stimulation associated with this type of contraction, a high concentration of Ca^{2+} is maintained in the sarcoplasm. As for muscle stiffness, the above consideration regarding the interpretation of the twitch torque to isometric MVC ratio, also applies when using the ratio to categorize possible adaptations in the excitation contraction coupling processes.

The significant maximum rate of torque relaxation and the trend observed toward an increase in maximum rate of torque development in the EF, may suggest possible adaptations in the rate of uptake and release of Ca^{2+} from the SR. Very little is known about how exercise could affect the Ca^{2+} sequestration by the SR (Klug and Tibbits, 1988). However, the high variation observed for the day to day and trial to trial reliability (appendix A), for some of these time-related contractile properties, suggest that caution should be exercised before interpreting changes in these properties as training adaptations of cellular mechanisms.

One indirect way of measuring the effect of resistance training on muscle stiffness is to compare the relative (% pre-test) increases in twitch torque at joint angles of highest and lowest flexion. However, in order to use twitch torque as a valid indicator of stiffness, some assumptions have to be made. First, it is assumed that the moment arm at the joint angle at the pre- and post-test were similar. Second, that the active state dictated by the sliding filament theory of muscle contraction (Gordon et al., 1966), and the effect of muscle length on Ca^{2+} concentration in the sarcoplasm and fiber sensitivity to Ca^{2+} (Stephenson and Wendt, 1984), were also similar at pre- and post-test.

A change in muscle stiffness should affect, to agreater extent, the twitch torque produced at joint angles of greatest flexion. At these joint angles, the slack in the series elastic elements is higher, so that twitch torque will be more sensitive to an increase in muscle stiffness. In the present study, no differences in the relative changes in twitch torque were observed for the EF, between the 4 joint angles of contraction. On the contrary, the relative % change in torque at joint angle 150°, although not significantly different was 11 % higher than the relative % change at an angle of 80°.

While changes in muscle stiffness may have been a contributing factor, it is suggested that alterations in excitation-contraction coupling represent the major mechanism responsible for the increase in twitch torque, observed in this study.

D. Time-course of strength adaptations

The time course of the strength adaptations varied with the muscle groups and the mode of testing used. Significant increases in voluntary strength were observed during both training phases for all upper body testing, including the 1 RM performance measures (bench press and arm curl), the EF maximum voluntary isometric and isokinetic peak torques.

For the knee extensors, including the 1 RM performance measures (leg press) and the maximum voluntary isokinetic peak torque, a significant increase in strength occurred only during the first phase of training. The double leg extension measured in the experimental group only, displayed an increase in strength during both training phases, although the increase during the second phase was very close to the critical value (Tukey post-hoc test) necessary to obtain significance. The increase in voluntary isometric peak torque of the knee extensors at a joint angle of 90° occurred during both phases of training. However at 120°, only the first phase of training contributed to a significant gain in strength. Finally, for the twitch torque of both elbow flexors and knee extensors, significant gains in strength were achieved only during the second 10 weeks of training.

These results may suggest that the knee extensors were at a higher level of voluntary strength at the beginning of the study than the upper body muscles. This difference in training status between upper and lower body could explain why the legs reached a plateau in strength by the mid-point of training. The quadriceps, by it's weight bearing role during habitual activity is more likely to be at a higher initial level of training than the upper body muscles which are used less frequently on an habitual basis. In addition, the insignificant increase in voluntary peak isometric torque of the knee extensors at joint angles of 140° and 160° suggest that the training effect resulting from the boys daily activities, such as running and cycling, is more specific (Gardner, 1963; Lindh, 1979) to joint angles of greatest extension.

While this may explain the difference between the upper and lower body limbs for voluntary strength, it does not explain the significant increase in KE twitch torque, in the latter part of training. O'Hagan (1987) observed a significant increase in twitch torque of the EF after 14 weeks of resistance training. By 20 weeks, the final value, although still significantly greater than the pre-training value, had significantly decreased.

In the present investigation, after 10 weeks of training, the EF at the three joint angles of greatest flexion (80°,100° and 120°) displayed a non-significant pattern of decreased twitch torque. It is unlikely, that training is responsible for this trend, since the same pattern was observed for the control group at the same three joint angles. Furthermore, the difference in absolute terms represents less than 0.2 N·m. The same observation was not made for KE twitch torque, observed at the single joint angle of 90°. The time-course of twitch torque adaptations observed in the present study for the EF and KE remains to be confirmed.

E. Neural adaptations to training

While there was a tendency for % motor unit activation (MUA) to increase with training, no significant differences were observed between pre- and post-scores for either elbow flexors and knee extensors. The initial level of activation combining both experimental and control groups was estimated at 89 and 78 % for the elbow flexors and knee extensors, respectively, showing high activation in these prepubescent children, particularly for the elbow flexors. Some variation was observed within subjects during the three testing periods for % MUA. A lack of motivation on the part of the subject could explain in part, this variation in activation.

The level of activation for the elbow flexors was similar to that of 16 year old boys, while the level of activation for the knee extensors was somewhat lower (Blimkie, 1989 - in press). In adults, full motor unit activation was observed for the bicep brachii (Bellemare et al., 1983) and the quadriceps (Chapman et al., 1984) of untrained subjects.

While studies investigating motor unit activation, in adults, using the interpolated twitch technique have shown that full motor unit activation can be achieved in most muscles of untrained adult subjects (Belanger and McComas, 1981; Chapman et al., 1984; Kukulka et al., 1986; Rutherford and Jones, 1986), it has been suggested that activities such as resistance training may increase the degree of motor unit activation (for a review see Sale, 1987 and 1988). There is evidence that not all muscles can be fully activated (Belanger & McComas, 1981).

The percent increases were 13.2 % and 17.4 % for the elbow flexors and knee extensors, of the experimental groups. Percent motor unit activation of the elbow flexors for the control group was identical for all three measurement periods. These results suggest that the increase in strength can only partly be attributed to an increase in motor unit activation. This does not preclude, however, the possible enhancing effect of training on other specific neurological adaptations within the prime movers which were not assessed with this technique.

While the interpolation technique offers an easy way of measuring motor unit activation, it does have certain limitations. Belanger and McComas (1981) using this technique observed that further torque could be developed during dorsi-flexion, despite full motor unit activation in the tibialis anterior. A possible reason is that while the technique indicates whether all motor units are recruited, it may fail to show if all these motor units are firing at the optimal firing frequency for maximum torque development (Sale, 1987). A second possibility is that the interpolated twitch stimulus may fail to reach the muscle because the axons, due to the high level of voluntary efferent activity to the motor unit pool, have become refractory (Sale, 1987).

Since the training program involved both the double leg press and arm curl, it is probable that the training increases in 1 RM performance and isokinetic strength observed in this study could, at least in part, be attributed to learning of a patterned motion. The size of the strength gains over the entire study and the increases in strength made during the second phase of the training for many of the muscle groups, makes it unlikely however that this is the only factor involved. Training may have resulted in other neurological adaptations such as a more appropriate co-contraction of synergists and increased inhibition of antagonists favoring an increase in strength (Sale, 1987). The determination of adaptations in synergist and antagonist muscle activity using electromyography could provide interesting information concerning the importance of these factors to training induced strength increases.

An increased synchronization of motor unit firing (Milner-Brown et al., 1975) represents another possible adaptation to training. However, since equal force output can be developed during maximal voluntary contraction with synchronous and asynchronous discharge of motor units, the precise role played by this increased synchronization remains to be determined (Sale, 1987). It has been suggested that synchronization may increase the rate of force development for very brief and rapid contractions (Sale, 1987).

Finally, training could have increased the excitability of the motoneuron pool, enabling the trained subject to reach the pre-training torque output with a decreased neural drive. However, Sale et al. (1983) reported (unpublished observations) no evidence of an increased H-reflex at rest in strength trained athletes.

In conclusion, it appears that 20 weeks of weight training significantly increased strength in prepubescent boys. Although strength increases were independent of changes in muscle cross-sectional area as measured by CAT, significant increases in twitch torque were observed for both elbow flexors and knee extensors. These observations combined with a trend toward increased maximum rate of torque development suggest adaptations in excitation-contraction coupling processes. While only a trend in increased % motor unit activation was observed, the results suggested that specific neurological adaptations also contributed to the observed strength increases following 20 weeks of resistance training in this study.

REFERENCES

Alexander, H.W.. A general test for trend. Psychological Bulletin, XLIII,1946, pp. 533-557.

Alway, S.E.. The effects of training on muscle structure and function in the human triceps surae. Unpublished doctoral dissertation, McMaster University, 1985.

Alway, S.E., MacDougall, J.D., Sale, D.G. and J.R. Sutton. Structural and contractile adaptations to isometric training in man. Med. Sci. Sports Exerc., 18 : (Suppl. 552), S22, 1986.

Baumgartner, T.A. and A.S. Jackson. Measurement for evaluation in physical education. Boston, Houghton Mifflin Company, 1975.

Belanger, A.Y. and A.J. McComas. Extent of motor unit activation during effort. Journal of Applied Physiology, 51 : 1131-1135, 1981.

Bell, R.D., MacDougall, J.D., Billeter, R. and H. Howald. Muscle fiber types and morphometric analysis of skeletal muscle in six year-old children. Med. Sci. Sports Exerc., 12 : 28-31, 1980.

Bellemare, F., Woods, J.J., Johansson, R. and B. Bigland-Ritchie. Motor-unit discharge rates in maximal voluntary contractions of three human muscles. J. Neurophysiol., 50 : 1380-1392, 1983.

Berger, R.A.. Comparative effects of three weight training programs. Res. Quart., 43 : 396-398, 1963.

Bigland-Ritchie, B.. EMG/force relations and fatigue of human voluntary contractions. Exercise Sport Sciences Reviews, 9 : 75-117, 1981.

Blimkie, C.J.R.. Development of gas transport capacity in boys. Unpublished doctoral dissertation, Western University, 1982.

Blimkie, C.J.R.. Age- and sex-associated variation in strength during childhood : anthopometric, morphologic, neurologic, biomechanical, endocrinologic, genetic and physical activity correlates. In D. Lamb and C. Gisalfi (eds.), Perspective in exercise science and sport medecine, vol. II youth, exercise and sport. 1989, in press.

Blinks, J.R., Rudel, R. and S.R. Taylor. Calcium transients in isolated amphibian skeletal muscle fibres: detection with aquorin. J. Physiol., 277 : 291-323, 1978.

Brown, C.H. and J.H. Wilmore. Effects of maximal resistance training on the strength and body composition of women athletes. Med. Sci. Sports, 6 : 174-177, 1974.

Caiozzo, V.J., Perrine J.J. and V.R. Edgerton. Training-induced alterations of the in-vivo force-velocity relationship of human muscle. J. Appl. Physiol., 51 : 750-754, 1981.

Cannon, R.J. and E. Cafarelli. Neuromuscular adaptations to training. J. Appl. Physiol., 63 : 2396-2402, 1987.

Chapman, S.J., Grindrod, S.R. and D.A. Jones. Cross-sectional area and force production of the quadriceps muscle. J. Physiol., 353, 53P, 1984.

Close, R.I.. Dynamic properties of mammilian skeletal muscle. Physiol. Reviews, 52 : 129-197, 1972.

Costill, D.L., Coyle, E.F., Fink, W.F. Lesmes, G.K. and F.A. Witzmann. Adaptations in skeletal muscle following strength training. J. Appl. Physiol., 46 : 96-99, 1979.

Coyle, E.F., Feiring D.C., Rotkis T.C., Cote, R.W., Roby F., Lee W. and J. Wilmore. Specificity of power improvements through slow and fast isokinetic training. J. Appl. Physiol., 51 : 1437-1442, 1981.

Cureton, K.J., Collins M.A., Hill D.W. and F.M. McElhannon Jr. Muscle hypertrophy in men and women. Med. Sci Sports Exerc., 20 : 338-343, 1988.

Davies, C. and K. McGrath. Effect of training and chronic (40 Hz) stimulation on voluntary and electrically evoked contractions of the triceps surae in a human subject. J. Physiol., 329 : 48-49P, 1982.

Davies, C. and K. Young. Effects of training at 30 % and 100% maximal isometric force (MVC) on the contractile properties of the triceps surae in man. J. Physiol., 336 : 31P, 1983.

Davies, C.T.M., Dooley, P., McDonagh, M.J.N. and M.J. White. Adaptation of mechanical properties of muscle to high force training in man. J. Physiol., 365: 277-284, 1985.

DeKoning, F.L., Binkhorst, R.A., Vissers, A.C.A.and J.A. Vos. The influence of static strength training on the force-velocity relationship of the arm flexors of 16-year-old boys. In Hamarian, J. and I. Vitinniski (eds.), Children and Sport Pediatric Work Physiology, New York, Spinger-Verlag, 1984, pp. 201-205.

DeLorme, T. and A. Watkins. Techniques of progressive resistance exercise. Arch. Phys. Med. Rehabil., 29 : 263-273, 1948.

DeLorme, T.L., Ferris B.G. and J.R. Roswell. Effect of progressive resistance exercise on muscle contraction time. Arch. Phys. Med. Rehab., 33 : 86-92, 1952.

Denny-Brown D. On inhibition as a reflex accompaniment of the tendonjerk and other forms of muscular activity. Proc. Roy. Soc. B., 103 : 321-336, 1928.

Desmedt, J.E. and E. Godaux. Voluntary motor commands in human ballistic movements. Ann. Neurol., 5 : 415-421, 1979.

Desouza, K.. Quadriceps inhibition post arthroscopic menisectomy. Unpublished master dissertation, McMaster University, 1987.

Docherty, D., Wenger, H.A., Collis, M.L. and H.A. Quinney. The effects of variable speed resistance training on prepubertal boys. Can. J. Appl. Sports Sci., 9 : 11, 1984.

Dons B., Bollerup K., Bonde-Petersen, F. and S Hancke. The effect of weight-lifting exercise related to muscle fibre composition and muscle cross-sectional area in humans. Eur. J. Appl. Physiol., 40 : 95-106, 1979.

Duchateau, J. and K. Hainaut. Isometric or dynamic training: differential effects on mechanical properties of a human muscle. J. Appl. Physiol., 56 : 296-301, 1984.

Edwards, R.H.T., Chapman S.J., Newham D.J. and D.A. Jones. Practical analysis of variability of muscle function measurements in Duchenne muscular dystrophy. Muscle Nerve, 10 : 6-14, 1987.

Eisenhart C.. Expression of the uncertainties of final results. Science, 160 : 1201-1204, 1968.

Eisenberg, B.R.. Quantitative ultrastucture of mammilian skeletal muscle. In Peachy, L.D., Adrian R.H. and S.R. Geiger (eds) : Handbook of Physiology Skeletal Muscle, Baltimore, William and Wilkins, 1983, pp. 773-112.

Elder G.C.B., Bradbury K., and R. Roberts. Variability of fiber distribution within human muscles. J. Appl. Physiol., 53 : 1473-1480, 1982.

Fahey, T.D.R., Rolph R., Moungmee, P., Nagel J. and S. Mortara. Serum testosterone, body composition, and strength of young adults. Med. Sci. Sports, 8 : 31-34, 1976.

Friman, G.. Effect of acute infectious disease on isometric muscle strength. Scand. Clin. Lab. Invest., 37 : 303-308.

Frank, B.D.. Measurement and evaluation. In Zeigler, E.F. (ed.). Physical education and sport : an introduction. Philadelphia, Lea and Febiger, 1982.

Funato, K., Fukunaga, T., Asami T. and I. Shigeharu. Strength training for prepubescent boys and girls. Proc. Dept. Sports Science, Univ. Tokyo, 21 : 9-19, 1987.

Galbo, H.. Endocrinology and metabolism in exercise. Int. J. Sports Med., 2 : 203-211, 1981.

Galbo, H.. Hormonal and metabolic adaptation to exercise. New York, Thieme-Stratton Inc., 1983, pp. 1-116.

Goldberg, A.L., Etlinger J.D., Goldspink, D.F. and C. Jablecki. Mechanism of work-induced hypertrophy of skeletal muscle. Med. Sci. Sports, 7 : 185-198, 1975.

Gallagher, J.R. and T.L. DeLorme. The use of the technique of progressive-resistance exercise in adolescence. J. Bon. Joint Surg., 31-A : 847-858, 1949.

Gollnick, P.D., Karlsson, J., Piehl, K. and B. Saltin. Selective glycogen depletion in skeletal muscle fibres of man following sustained contraction. J. Physiol., 241 : 59-67, 1974.

Gordon, A.M., Huxley, A.F. and F.J. Julian. The variation in isometric tension with sarcomere length in vertebrate muscle fibres. J. Physiol., 184 : 170-192, 1966.

Grimby, L., Hannerz, J., and B. Hedman. The fatigue and voluntary discharge properties of single motor units in man. J. Physiol., 316 : 545-554, 1981.

Haggmark, T., Jansson, E. and B. Svane. Cross-sectional area of the thigh muscle in man measured by computed tomography. Scand. J. Lab. Invest., 38 : 355-360, 1978.

Haines, D. Physical fitness of Canadian youth, 1985.

Hakkinen, K.. Factors influencing trainability of muscular strength during short term and prolonged training. National Strength Coach Association J., 7 : 32-37, 1985.

Hakkinen, K., Komi, P.V. and P.A. Tesch. Effect of combined concentric and eccentric strength training and detraining on force-time, muscle fibre, and metabolic characteristics of leg extensor muscles. Scand. J. Sports Sci., 3 : 50-58, 1981.

Hakkinen, K. and P. Komi. Electromyographic and mechanical characteristics of human skeletal muscles during fatigue under voluntary and reflex condition. Electroencephal. Clin. Neurophysiol., 55 : 436-444, 1983.

Hakkinen, K. and P. Komi. Electromyographic changes during strength training and detraining. Med. Sci. Sports Exerc, 15 : 455-460, 1983.

Hakkinen, K., Alen M. and P. Komi. Changes in isometric force and relaxation time, electromyographic and muscle fibre characteristics of human skeletal muscle during strength training and detraining. Acta Physiol. Scand., 125 : 573- 585, 1985.

Hakkinen, K. and P. Komi. Training induced changes in neuromuscular performance under voluntary and reflex conditions. Eur. J. Appl. Physiol., 55 : 147-155, 1986.

Hetrick, G.A. and J.H. Wilmore. Androgen levels and muscle hypertrophy during an eight week weight training program for men/women. Med. Sci. Sports, 11 : 102, 1979.

Henneman, E., Somjen G. and D.C. Carpenter. Functional significance of cell size in spinal motoneurons. J. Neurophysiol., 28 : 560-580, 1965.

Houston, M.E., Green H.J. and J.T. Stull. Myosin light chain phosphorylation and twitch potentiation in intact human muscle. Pflugers Arch., 403 : 348-352, 1985.

Hudash, G., Albright J.P., McAuley E., Martin R.K. and M. Fulton. Cross-sectional thigh component tomographic assessment. Med. Sci. Sports Exerc., 17 : 417-421, 1985.

Ikai M. and T. Fukunaga. A study on training effect on strength per unit cross-sectional area of muscle by means of ultrasonic measurement. Int. Z. angew. Physiol., 28 : 173- 180, 1970.

Kanehisa, H. and M. Miyashita. Effect of isometric and isokinetic muscle training on static strength and dynamic power. Eur. J. Appl. Physiol., 50 : 365-371, 1983a.

Kanehisa, H. and M. Miyashita. Specificity of velocity in strength training. Eur. J. Appl. Physiol., 52 : 104-106, 1983b.

Kaufman, T.L.. Strength training effect in young and aged women. Arch. Phys. Med. Rehab., 65 : 223-226, 1985.

Klug, G.A. and G.F. Tibbits. The effect of activity on calcium mediated events in striated muscle. In Pandolf, K.B. (ed.). Exercise and Sport Sciences Reviews. New York, MacMillan Publis. Comp., 1988, pp. 1-59.

Koehler, R., Anderson, R.E. and B. Baxter. The effect of computed tomography viewer controls on anatomical measurements. Radiology, 130 : 189-194, 1979.

Komi, P.. Training of muscle strength and power : interaction of neuromotoric, hypertrophic and mechanical factors. Int. J Sports Med.,7 : 10-15, 1986.

Komi, P.V., Karlsson, J., Tesch, P., Suominen, H. and E. Heikinen. Effects of heavy resistance and explosive type strength methods on mechanical, functional and metabolic aspects of performance. In Komi, P.V. (ed), Exercise and Sport Biology, Champaign, Human Kinetics, 1982, pp. 90-102.

Kraemer, W.J. and S.J. Fleck. Resistance training : exercise prescription part 4 of 4). The Physician and Sportmedecine, 16 : 69-81, 1987.

Kroll W.. A note on the coefficient of intraclass correlation as an estimate of reliability. Res. Quat., 33 : 313-316, 1962.

Krotkiewski, L., A. Aniansson, G. Grimby, P. Bjorntorp and L. Sjostrom. The effect of unilateral isokinetic training on local adipose and muscle tissue morphology, thickness and enzymes. Eur. J. Appl. Physiol., 42 : 271-181, 1979.

Kukulka, C.G. and H.P. Clamman. Comparison of the recruitment and discharge properties of motor units in human brachial biceps and adductor pollicis during isometric contractions. Brain Res., 219 : 45-55, 1981.

Kusinitz I. and C.E. Keeney. Effects of progressive weight training on health and physical fitness of adolescent boys. Res. Quat., 29 : 294-301, 1958.

Lamb, D.R.. Androgens and exercise. Med. Sci. Sports, 7 : 1-5, 1975.

Lambert, O.. The relationship between maximum isometric strength and maximum concentric strength at different speeds. Intern. Fed. Phys. Educ. Bull., 35 : 13, 1965.

Lesmes, G.R., Costill, D.L., Coyle and W.J. Fink. Muscle strength and power changes during maximal isokinetic training. Med. Sci. Sports Exerc., 10 : 266-269, 1978.

Liberson, W.T. and M.M. Asa. Further studies of brief isometric exercises. Arc. Phys. Med. Reh., 40 : 330-336, 1959.

Lindh, M.. Increase of muscle strength from isometric quadriceps exercise at different knee angles. Scand. J. Rehabil. Med., 11 : 33-36, 1979.

Lohman, T. G., Slaughter, M.H., Boileau, R.G., Bunt, J. and L. Lussier. Bone mineral measurements and their relation to body density in children, youth and adults. Human Biology, 56 : 667-679, 1984

Luthi, J.M., Howald H., Claassen H., Rosier K., Vock P. and H. Hoppeler. Structural changes in skeletal muscle tissue with heavy resistance exercise. Int. J. Sports

Med., 7 : 123-127, 1986.

MacDougall, J.D., Ward, G.R., Sale, D.G. and J.R. Sutton. Biochemical adaptation of human skeletal muscle to heavy resistance training and immobilization. J. Appl. Physiol., 43 : 700-703, 1977.

MacDougall, J.D., Sale, D.G., Moroz, J.R., Elder, G.C.B., Sutton, J.R. and H. Howald. Mitochondrial volume density in human skeletal muscle following heavy resistance training. Med. Sci. Sports Exerc., 11 : 164-166, 1979.

MacDougall, J.D., Sale, D.G. Moroz, J.R. and J.R. Sutton. Effect of strength training and immobilization on human muscle fibers. Eur. J. Appl. Physiol., 43 : 25-34, 1980.

MacDougall, J.D., Sale, D.G., Elder, G.C.B. and J.R. Sutton. Muscle ultrastructural characteristics of elite powerlifters and bodybuilders. Eur. J. Appl. Physiol., 48 : 117-126, 1982.

Malina, R. M. Anthropometric correlates of strength and motor performance. Exercise and Sport Sciences Reviews, 3 : 249-274, 1975.

Maughan, R.J. and M.A. Nimmo. The influence of variations in muscle fibrecomposition on muscle strength and cross-sectional area in untrained males. J. Physiol., 351 : 299-311, 1984a.

Maughan, R.J. Relationship between muscle strength and muscle cross-sectional area, Implications for training. Sports Med., 1 : 263-269, 1984b.

McCullough, E. Factors affecting the use of quantitative information from CT scanner. Radiology, 124 : 99-107, 1977.

McDonagh, M.J.N., Hayward, C.M. and C.T.M. Davies. Isometric training in human elbow flexor muscles. J. Bone Joint Surg., 65 : 355-358, 1983.

McDonagh, M.J.N. and C.T.M. Davies. Adaptive response of mammalian muscle to exercise with high loads. Eur. J. Appl. Physiol., 52 : 139-155, 1984.

McGovern, M.B.. Effects of circuit weight training on the physical fitness of prepubescent children. Diss. Abst.Inter., 45 : 452-A, 1984.

Merton, P.A.. Voluntary strength and fatigue. J. of Physiol., 123 : 553-564, 1954

Milner-Brown, H., R. Stein and R. Yemm. Synchronization of human motor units : Possible roles of exercises and supraspinal reflexes. Electroencephal. Clin. Neurophysiol., 38 : 245- 254, 1975.

Moffroid, M.A., Whipple R., Hofkosh, J., Lowman E. and H. Thistle. A study of isokinetic exercise. Phys. Ther., 49 : 735-747, 1969.

Moffroid, M.A. and R. Whipple. Specificity of velocity in strength training. Phys. Ther., 50 : 1693-1699, 1970.

Moritani, T. and H. deVries. Neural factors vs. hypertrophy in time course of muscle strength gain. Amer. J. Phys. Med. Rehabil., 58 : 115-130, 1979.

Moritani, T. and H.A. deVries. Potential for gross muscle hypertrophy in older men. J. Geront., 35 : 672-682, 1980.

Moritani, T. and M. Muro. Motor unit activity and surface electromyogram power spectrum during increasing force of contraction. Eur. J. Appl. Physiol., 56 : 260-265, 1987.

Moore, R.L. and J.T. Stull. Myosin light chain phosphorylation in fast and slow skeletal muscles in situ. Am. J. Physiol., 247: C462-C471, 1984.

Nielsen, B., Nielsen K., Hansen Behrendt M. and E. Asmussen. Training of "functional muscular strength" in girls 7-19 years old. In Binkhorst, R.A. (ed.). Children and Exercise IX, Champaign, Human Kinetics, 1980, pp. 69-78.

O'Hagan, F.T. The effect of isokinetic and weight training in young men and women. Unpublished master dissertation, McMaster University, 1987.

O'Shea, J.P.. Effects of selected weight training programs on the development of strength and muscle hypertrophy. Res. Quat., 37 : 97-102, 1966.

Pfeiffer, R.D. and R. S. Francis. Effects of strength training on muscle development in prepubescent, pubescent and postpubescent males. The Physician and Sportsmedecine, 14 : 134-143, 1986.

Rohmert, W.. Rechts-Links-Vergleich bei isometrischen Armmuskeltraining mit verchiedenem Trainingsreiz bei achtjahrigen Kindern. Int. Z. angew. Physiol. einschl. Arbeitsphysiol, 26 ; 363-393, 1968.

Rutherford, O.M. and D.A. Jones. The role of learning and co-ordination in strength training. Eur. J. Appl. Physiol., 55: 100-105, 1986.

Safrit, M.. Evaluation in Physical Education. Englewood Cliffs, N.J., Prentice Hall, 1973.

Sailors, M. and K. Berg. Comparison of responses to weight training in pubescent boys and men. J. Sports Med., 27 : 30-37, 1987.

Sale, D.G.. The effects of training and immobilization upon neuromuscular function in man. Unpublished doctoral dissertation. McMaster University, 1979.

Sale, D.G.. Neural adaptation in strength and power training. In Jones,N.L., McCartney, N. and A.J. McComas (eds.). Human Muscle Power. Champaign, Ill. : Human Kinetics, 1986, pp. 281-305.

Sale, D.G.. Influence of exercise and training on motor unit activation. In Pandolf, K.B. (ed.). Exercise and Sport Sciences Reviews. New York, MacMillan Publis. Comp., 1987, pp. 95-151.

Sale, D.G.. Strength training in children. In D. Lamb and C. Gisalfi (eds.), Perspective in exercise science and sport medecine, vol. II youth, exercise and sport. 1989, in press.

Sale, D.G., McComas, A.J., MacDougall, J.D. and A.R.M. Upton. Neuromuscular adaptation in human thenar muscles following strength training and immobilization. J. Appl. Physiol., 53 : 419-424, 1982a.

Sale, D.G. and R.W. Norman. Testing strength and power. In MacDougall, J.D., Green, H.J. and H.A. Wenger (eds.). Physiological testing of the elite athlete. Ottawa, Canadian Association of Sport Sciences, 1982b, pp. 7-38.

Sale, D.G., MacDougall J.D., Upton A. and A. McComas. Effect of strength training upon motoneuron excitability in man. Med. Sci. Sports Exerc., 15 : 57-62, 1983a.

Sale D.G., Upton A.R.M., McComas A.J. and J.D. MacDougall. Neuromuscular function in weight trainers. Exp. Neur., 82 : 521-531, 1983b.

Sale, D.G., MacDougall J.D., Alway S.E. and J.R. Sutton. Voluntary strength and muscle characteristics in untrained men and women and male bodybuilders. J. Appl. Physiol., 62 : 1786-1793, 1987.

Schantz, P., Randall-Fox, E., Hutchison W., Tyden A. and P.O. Astrand. Muscle fibre distribution, muscle cross-sectional area and maximal voluntary strength in humans. Acta Physiol. Scand., 117 : 219-226, 1983.

Seaborne D. and A.W. Taylor. The effects of isokinetic exercise on vastus lateralis fibre morphology and biochemistry. J. Sports Med., 21 : 365-370, 1981.

Servedio, F.J., Bartels, R.L., Hamlin, R.L., Teske, D., Shaffer, T. and A. Servedio. The effects of weight training, using olympic style lifts, on various physiological variables in pre-pubescent boys. Med. Sci. Sports and Exerc., 17 : 288, 1985.

Sewall, L. and L.J. Micheli. Strength training for children. J.Ped. Orth., 6 : 143-146, 1986.

Siegel, J.A., Camaione D.N. and T.G. Manfredi. Upper body strength training and prepubescent children. Med. Sci. Sports Exerc., 20 : S52, 1988.

Smith, M.J. and P. Melton. Isokinetic versus isotonic variable- resistance training. Amer. J. Sports Med., 9 : 275-279, 1981.

Steben, R.E. and A.H. Steben. The validity of the stretch shortening cycle in selected jumping events. J. Sports Med., 21 : 28-37, 1981.

Stephenson, D.G. and I.R. Wendt. Length dependence of changes in sarcoplasmic calcium concentration and myofibrillar calcium sensitivity in striated muscle fibres. J. Musc. Res. Cell Motility, 5 : 243-272, 1984.

Tanner, J.M.. Growth and adolescence. Second Edition, Blackwell Scientific Publishers, 1962.

Thomas, J.R. and J.K. Nelson. Introduction to research in health, Physical Education, Recreation, and Dance, Champaign, Human Kinetics Publishers Inc., 1985.

Thorstensson A., Hulten B., Dobeln W.V. and J, Karlsson. Effect of strength training on enzyme activities and fibre characteristics in human skeletal muscle. Acta Physiol. Scand., 96 : 392-398, 1976a.

Thorstensson A., Karlsson J. Vittasalo, J.H.T., Luhtanen P. and P. Komi. Effect of strength training on EMG of human skeletal muscle. Acta. Physiol. Scand., 98 : 232-236, 1976b.

Vandervoort, A.. Unilateral and bilateral muscle contraction in man. Unpublished master dissertation, McMaster University, 1982.

Vandervoort, A.A., Sale D.G. and J.R. Moroz. Comparison of motor unit activation during unilateral and bilateral leg extension. J. Appl. Physiol., 56 : 46-51, 1984.

Vandervoort, A.A., Sale D.G. and J.R. Moroz. Strength-velocity relationship and fatiguability of unilateral versus bilateral arm extension. Eur. J. Physiol., 56 : 201-205, 1987.

Vanhelder, W.P., Radomski, M.W.and R.C. Coode. Growth hormone responses during intermittent weight lifting exercise in men. Eur. J. Appl. Physiol., 53 : 31-34, 1984.

Vanhelder, W.P., Radomski, M.W., Coode R.C. and K. Casey. Hormonal and metabolic response to three types of exercise of equal duration and external work output. Eur. J. Appl. Physiol., 54 : 337-342, 1985.

Vrijens, J.. Muscle strength development in the pre- and post-pubescent age. Med. Sports, 11 : 152-158, 1978.

Weiss, L.W., Kirk, C.J. and F.N. Thompson. Comparison of serum testosterone and androstenedione responses to weight lifting in men and women. Eur. J. Appl. Physiol., 50 : 413-119, 1983.

Weltman, A., Janny, C., Rians, C.B., Strand, K., Berg, B. Tippitt, S., Wise, J., Cahill, B.R. and F.I. Katch. The effects of hydraulic resistance strength training in pre-pubertal males. Med. Sci. Sports Exerc., 18 : 629-638, 1986.

Westerlind, K.C., Byrnes, W.C., Freedson, P.S. and F.I. Katch. Exercise and serum androgens in women. The Physician and Sportmedecine, 15 : 87-94, 1987.

Winter, J.S.D.. Prepubertal and pubertal endocrinology. In F. Falkner and J.M. Tanner (Eds.). Human Growth. 2. Postnatal Growth. New York, Plenum Press, 1978, pp. 182-213.

Young, A., Stokes, M., Round, J.M. and R.H. Edwards. The effect of high resistance training on the strength and cross-sectional area of the human quadriceps. Eur. J. Clin. Invest., 3 : 411-417, 1983.

DEFINITION OF TERMS

Adaptation : biological changes that occur in response to a stimulus, in this case resistance training.

Concentric contraction : muscle shortening under tension. This shortening occurs when the net moment developed by a muscle and it's synergists is greater than the moment caused by the external forces acting on the segment to which the muscle is attached.

Contraction : A voluntary or involuntary shortening by a muscle resulting in a reduction in the distance between the two ends of a muscle.

Digitizer : a device that is capable of acquiring planar coordinates in numerical form. In the study of human hypertrophy, the use of a digitizer is to convert the location of coordinates along the periphery of a muscle cross-sectional area into numbers that can be processed by a computer.

Eccentric muscle action : muscle lengthening under tension. This lenghening occurs when the external force acting on the segment to which a muscle is attached causes a net moment that is greater than the moment that is being developed by the muscle and its synergists. Note: the use of the term "contraction" is inappropriate for this type of muscle action.

Electrode : A conducting device used to record an electric potential(recording electrode) or to apply an electric current (stimulating electrode).

Electromyography (EMG) : The recording and study of spontaneous, and voluntary electric activity of muscle.

Firing rate : the level of activation or discharge frequency of recruited motor units.

Frequency of training : represents the number of training sessions for a given period, normally a week.

Half-relaxation time : the elapsed time from the occurrance of peak torque to half the peak torque during the relaxation of a muscle twitch contraction.

Intensity of training : determined by the load (% 1 RM), the volume of training, the method of training and the type and sequence of the exercises.

Interpolated twitch : a technique used to measure the degree of motor unit activation. A supra-maximal twitch is applied during the peak of a maximal voluntary contraction. The increment in force above that generated by the voluntary contraction enables estimation of the % motor unit activation.

Isokinetic muscle action : muscle action in which the rate of shortening or lengthening of the muscle is constant. Because joint geometry makes this impossible to determine in vivo, the definition is usually relaxed to apply either to a constant velocity of the load being lifted or resisted or to a constant angular velocity of the joint.

Isometric muscle action : muscle action in which the rate of shortening or lengthening of the muscle is constant. The action of a muscle when no change exists in the distance between its points of attachment-referring to the joint and not the muscle.

Isotonic muscle action : muscle action that involves the production of a constant force. For in vivo muscle actions, the term is also commonly used both when the joint moment is constant over a range of motion and when a constant load is being moved through a distance. It is important to realize, however, that because of the leverage effects at the joint, the force developed by the muscles in both these cases will actually be changing, rendering them nonisotonic.

Load : a percentage of the one repetition maximum (1 RM) or the heaviest weight lifted for a maximum number of repetitions (e.g. 10 RM).

Maximum rate of torque development : the maximal rate of increase in torque development obtained by a muscle twitch, tetanic contraction or maximum voluntary contraction, following activation. Units are Newtons·second^{-1} ($N \cdot s^{-1}$).

Maximum rate of torque relaxation : the maximal rate of decrease intorque relaxation obtained by a muscle twitch, tetanic contraction or maximum voluntary contraction, following activation. Units are Newtons·second^{-1} ($N \cdot s^{-1}$).

Motor unit : the anatomic unit of an anterior horn cell, its axon, the neuromuscular junctions, and all of the muscle fibres innervated by the axon.

Muscular endurance : the number of repetitions performed by a subject at the end of the training period, for a given exercise, with the pre-training one repetition maximum (1 RM).

Overloading : subjecting the neuromuscular system to a high functional demand in order to force adaptation(s).

Peak torque : the greatest torque developed during a maximal concentric contraction. Units are Newton·metres (N·m)

Potentiation : the enhancement of a physiological response. Used to describe the increase in force output of muscle elicited by repetitive nerve stimulation or by a voluntary contraction.

Pre-puberty : the period of relatively constant rate of change in physical growth (height and weight) preceding the onset of puberty, which occurs in females around 11-12 years of age and in males around 13-14 years of age.

Puberty : the period marked by the beginning development of secondary sexcharacteristics and an abrupt increase in the rate of change in height.

Recruitment : the successive activation of the same and additional motor units with increasing strength of contraction.

Repetition : the number of times an exercise is done without resting during one set.

Repetition maximum (RM) : the maximal load that can be lifted for a given number of repetitions

Set : the completion of one exercise activity or a given number of repetitions performed consecutively.

Tetanic contraction : a muscle contraction produced through repetitive maximal direct or indirect stimulation at a sufficient high frequency to produce a smooth summation of successive maximum twitches. The term may also be applied to maximum voluntary contractions in which the firing frequencies of most or all of the component motor units are sufficienly high that successive twitches of individual motor units fuse smoothly.

Tetanus : the sustained contraction of muscle caused by repetitive stimulation or discharge of nerve or muscle.

Time to peak torque : the time between the beginning of a twitch and development of maximum torque. Units are milliseconds (ms).

Total Contraction Time : the time between the beginning of a twitch contraction and the point when the torque decreases to one half of the maximal torque attained during the contraction (Time to peak torque + half-relaxation time). Units are milliseconds (ms).

Twitch contraction : a muscle contraction produced by a single electricalstimulus. Units are newton·metres (N·m).

Volume of training : the number of exercises, number of sets and number of repetitions per set within a time period. Can also be expressed as the total force or weight lifted.

Appendix A

Reliability of Strength and Contractile Property Measurements

A measurement should display two essential characteristics before being used in a study. First, it should be valid, in other words, it must measure what it is supposed to measure. A second requirement is that it should show consistency in measuring a variable, this quality is termed the reliability of a measurement. While a measurement must be reliable to be valid, the opposite is not necessarily true.

Over the years, studies dealing with the effects of strength training on the neuromuscular system, have established the validity of the techniques used in the present study to measure strength and contractile properties of muscle. While the reliability of these techniques has been assessed for the adult population (Thorstensson ,1976 ; Sale, 1979 ; Vandervoort, 1982), no study has presented data concerning the reliability of these measurements for children. It was the purpose of this study to assess the reliability of the following strength-related measurements in prepubescent boys : (1) the 1 repetition maximum (1 RM) performance lifts, (2) isometric peak torque, (3) isokinetic peak torque, and (4) contractile properties of muscle.

The reliability of a test refers to the dependability of scores, their relative freedom from error variance (Safrit, 1973). It is defined as the amount of variation that occurs in test results between trials in one testing session (trial to trial variability), or in the results between two or more different days of testing (day to day variability) (Sale, 1982). A reliable test will give similar absolute scores for each person and will rank the persons in the same relative order both times (Frank, 1982). Baumgartner and Jackson (1975) have outlined 4 factors that can affect measurement error during testing : (1) the lack of agreement or consistency among scorers, (2) lack of consistent performance by the individual tested, also called the biological variation (Sale, 1982), (3) the failure of the instrument to measure consistently, and (4) the failure of the tester to follow standardized testing procedures.

This study examined two types of reliability ; the day to day or stability reliability and the trial to trial or the test-retest within a day reliability (Baumgartner and Jackson, 1975). The time interval between the testing sessions will depend on how strenuous the test is and how much time is needed by the subject for full recovery (

Thomas and Nelson, 1985). There is generally more consistency for the trial to trial than for the day to day reliability, the first yielding higher correlation coefficients (Thomas and Nelson, 1985).

METHODS

Six subjects (10.7 y ± 0.5) from the resistance training study volunteered for an additional day of testing in order to estimate the day to day reliability of the voluntary strength and contractile property measurements. Four of the six subjects were tested within a week following post-training testing. The remaining two subjects were tested within a week following testing, for another study examining the effects of detraining on strength adaptations, 10 weeks after the end of training.

Table 9 outlines the experimental variables for which day to day and trial to trial reliability were assessed. For the day to day reliability, the subjects were tested on two seperate days with at least 48 hours between testing sessions to allow for full recovery. For the performance measures (bench press and the leg press) the subjects were permitted an adequate warm-up and a certain number of near maximal intensity repetitions in order to reach the 1 repetition maximum. Since by definition the subjects could only reach peak performance once, it was not possible to determine the trial to trial reliability for the 1 RM performance measures. Consequently only the day to

Table 9. Measurements for reliability study including : a) voluntary strength and B) electrically evoked contractile properties.

EXPERIMENTAL VARIABLES FOR RELIABILITY STUDY

A) VOLUNTARY STRENGTH :

1) 1 REPETITION MAXIMUM : bench press and leg press
(Day to day reliability only)

	Elbow flexors	Knee extensors
2) ISOKINETIC STRENGTH :	0.52. and 3.14 $rad \cdot s^{-1}$	0.52 and 3.14 $rad \cdot s^{-1}$
3) ISOMETRIC STRENGTH :	100° and 150°	90° and 160°
B) ELECTRICALLY EVOKED CONTRACTILE PROPERTIES :	100°	160°

day reliability was measured and the maximum lift was used as the criterion score.

Peak isometric strength was measured for the elbow flexors at joint angles 100° and 150° and for the knee extensors at joint angles 90° and 160° (180° = full extension). Peak isokinetic strength was measured at velocities of contraction of 0.52 and 3.14 radian·second^{-1} for both limbs. These muscle groups were the same as those tested in the resistance training study. In the resistance training study, four angles and velocities were used for testing. For the reliability study, the two angles and velocities at each end of the range were used to provide a representative sample of variability due to angle or velocity of contraction. For the isometric and isokinetic peak torques and the contractile properties, the average of the best two trials out of three, on each day was used for analysis.

For the trial to trial reliability, the first and third trials on the second day of testing were chosen. With the exception of the performance strength measures, all other measures were taken on the right side of the body.

STATISTICAL ANALYSIS

Day to day and trial to trial reliability were estimated using three different statistical techniques.

First, the interclass correlation was measured using the Pearson product-moment correlation coefficient (r) which examines the linear dependance between two variables, in this case, the two days or the two trials. Many problems are associated with the use of this coefficient to determine the reliability of a test (Safrit, 1973 ; Baumgartner and Jackson, 1975 ; Thomas and Nelson, 1985).

While the interclass correlation coefficient was included in the figures, it is considered inappropriate for determination of reliability (Thomas and Nelson, 1985), since it estimates the relationship between two groups of scores that follow a bivariate distribution, in other words, two groups of scores that come from two different tests (Baumgartner and Jackson, 1975 ; Thomas and Nelson, 1985). The stability reliability and the test-retest within day reliability consist of measuring a subject on two consecutive occasions using the same test. This is referred to as an univariate situation. A second problem is that the interclass correlation does not take into account variations in means and standard deviations from one day or one trial to the other (Thomas and Nelson, 1985). In other words, the coefficient is sensitive to a change in the order of the scores, but not to a systematic change in the actual values of the scores from one day or from one trial to the other.

The second technique examined, the intraclass correlation, also referred to as the reproducibility of measurements by some researchers (Blimkie, 1982). The intraclass method considers variations in the mean and standard deviation from one set of measures to the next as measurement error or lack of reliability (Kroll, 1962). The correlation coefficient (R) of this method can be calculated from the results of a one-way analysis of variance with repeated measures (Thomas and Nelson, 1985).

The data must first be examined for trends using the F value derived from the analysis of variance :

$$F = \frac{MS_t}{MS_r}$$

where MS_t = mean square of the treatment and MS_r = mean square of the residual error. If the F value is not significant, this means that the difference between the two days or the two trials is not systematic (Safrit, 1973). In this case the estimation of the intraclass correlation coefficient is done using the mean square between subjects (MS_b) and the mean square for error (MS_e).

$$R = \frac{MS_b - MS_e}{MS_b}$$

The mean square for error is equal, in this case to the mean square within subjects (mean square treatment + mean square residual) and is computed as follows :

$$\frac{\text{SS for days + SS for interaction}}{\text{SS for days or trials + df for interaction}}$$

in which SS = the sum of squares and df = the degree of freedom of the within factor and of the interaction.

If a significant F is obtained, three choices are offered. First, the more conservative approach considers the day to day or trial to trial variance to be attributed to measurement error and consequently, part of the mean square error (Thomas and Nelson, 1985). Second, an adjusted formula for trend (Alexander, 1946) can be used. In this formula the mean square treatment is eliminated from the variance (within) so that the mean square error is made of only the mean square residual. One proplem with this approach is that variance within the individual is not considered,thus eliminating biological variation. An alternative is to omit the trial affected by trend and compute a new Anova with the remaining data. In the present investigation, this reduces the power of the Anova since only 6 subjects were used. Coefficients for all three methods will be presented for the measures showing a trend (significant F).

Finally a third method, the method error (ME) statistic which has been used in many studies dealing with physiological parameters was determined (Thortensson et al., 1976 ; Friman, 1977 ; Sale, 1979; Vandervoort, 1982).

It represents the standard deviation from the mean difference between days or trials. It is defined as the SD for a single experiment and it is calculated using the formula :

$$ME = \sqrt{(d-d)^2/2(n-1)}$$

in which d = the difference between the 2 measurements taken on each subject, d = the mean difference and n = the number of subjects. The ME can be expressed in absolute terms or as a coefficient of variation by using the following formula :

$$ME\ (CV) = \frac{ME}{(x_1 + x_2)\ /\ 2} \times 100$$

in which ME (CV) = method error expressed as a coefficient of variation, ME = the method error, x_1 = the mean result for the firt testing occasion and x_2 = the mean result for the second testing occasion.

Because of the advantages of the intraclass correlation, greater emphasis was given to this coefficient in the analysis of the results. The following categories were provided to assist in the interpretation of the intraclass and Pearson product-moment correlation coefficients.

Degree of Correlation

0-0.25 little

0.26-0.49 low

0.5-0.69 moderate

0.7-0.89 high

0.9-1.00 very high

Because of the small number of subjects and decreased power, the table of critical values of the correlation coefficient was used for both intraclass and interclass correlation coefficients. In the present investigation, coefficients lower than 0.729 ($p < 0.05$; df = n-2 =4) represented a non-significant relationship. Coefficients of 0.729 or more, meant that at least 53 % of the variance observed for one variable (first day or trial) could be explained by the other variable (second day or trial). Results displaying intraclass and interclass coefficients with values under 0.729 (high to very high degree of correlation) were not considered as a valid expression of reliability.

The Method error of measurement also received more consideration than the Pearson product moment correlation. In addition to testing for a systemic difference between days and trials, the ME when expressed as a coefficient of variation, allows comparison of the reliability of different types of physiological measurements (e.g.

strength versus contractile properties). A test with a coefficient of variation of 10 % or less was considered highly reliable.

RESULTS

The day to day reliability of upper and lower body voluntary strength measurements are presented in Tables 8 and 9, respectively.

Strength Performance Measurements

The 1 RM performance measures displayed a very high reliability for both the leg press ($R = 0.97$, $CV = 1.57$, $r = 0.96$) and the bench press ($R = 0.92$, $CV = 4.21$, $r = 0.9$). Note that the analysis of variance showed a significant difference between the means of the two testing days, indicating a trend in the data. The R of 0.97 was obtained for both trend correction procedures, using either the corrected formula or omitting one of the subjects (n=5) for the ANOVA. If no trend correction was made a R of 0.91 was found.

Peak Isometric Torque

The day to day reliability of isometric peak torque for the elbow flexors (EF) and knee extensors (KE) at the two joint angles ranged from high to very high ($0.84 < R < 0.98$; $4.34 < CV < 9.12$; $0.91 < r < 0.83$). The trial to

Table 10. Day to day reliability of voluntary upper-body strength measurements, including bench press, elbow flexor maximum isometric torque at joint angles of 100° and 150°, and elbow flexor maximum isokinetic torque at velocities of contraction of 0.52 and 3.14 $radian \cdot second^{-1}$. NS = non-significant. S = significant.

SUBJECT	BENCH PRESS (KG) DAY#1	BENCH PRESS (KG) DAY#2	ISOM. 100 (N·m) DAY#1	ISOM. 100 (N·m) DAY#2	ISOM. 150 (N·m) DAY#1	ISOM. 150 (N·m) DAY#2	ISOK. 0.52 rad/s DAY#1	ISOK. 0.52 rad/s DAY#2	ISOK. 3.14 rad/s DAY#1	ISOK. 3.14 rad/s DAY#2
1. N.C.	30.00	30.00	23.73	23.07	14.49	16.52	24.00	24.00	17.50	17.50
2. M.D.	32.50	35.00	24.12	24.03	12.52	14.09	22.00	16.88	19.50	12.50
3. P.C.	26.25	25.00	18.33	17.73	12.01	10.13	14.00	17.00	13.00	14.50
4. L.G.	25.00	26.25	25.47	26.37	14.97	18.27	21.00	19.50	18.00	16.00
5. S.N.	27.50	31.25	32.76	31.37	18.52	22.87	26.30	25.00	23.50	24.00
6. T.V.	25.00	25.00	18.67	21.78	11.71	13.75	20.50	27.75	17.12	24.00
MEAN	27.71	28.75	23.85	24.06	14.04	15.94	21.30	21.69	18.10	18.08
SEM	1.12	1.50	1.97	1.71	0.96	1.63	1.55	1.69	1.27	1.82
SD	2.74	3.68	4.82	4.18	2.35	4.00	3.80	4.14	3.12	4.45
ME	1.19		1.04		1.37		2.75		2.93	
CV (%)	4.21		4.34		9.12		12.80		16.18	
Pearson	r=0.90 (S)		r=0.96 (S)		r=0.95 (S)		r=0.52 (NS)		r=0.45 (NS)	
ANOVA	F=1.92 (NS) R=0.92 (S)		F=0.10 (NS) R=0.98 (S)		F=4.84 (NS) R=0.84 (S)		F=0.05 (NS) R=0.74 (S)		F=0.0 (NS) R=0.66 (NS)	

Table 11. Day to day reliability of voluntary strength measurements of the knee extensor muscles, including leg press, knee extensor maximum isometric torque at joint angles of 90° and 160°, and maximum isokinetic torque at velocities of contraction of 0.52 and 3.14 radian·second^{-1}. NS = non-significant. S = significant.

SUBJECT	LEG PRESS (KG) DAY#1	LEG PRESS (KG) DAY#2	ISOM. 90 (N·m) DAY#1	ISOM. 90 (N·m) DAY#2	ISOM. 160 (N·m) DAY#1	ISOM. 160 (N·m) DAY#2	ISOK. 0.52 rad/s DAY#1	ISOK. 0.52 rad/s DAY#2	ISOK. 3.14 rad/s DAY#1	ISOK. 3.14 rad/s DAY#2
1. N.C.	108.75	106.25	102.50	94.40	27.69	33.46	74.00	100.50	72.50	73.00
2. M.D.	110.00	108.75	86.90	113.20	35.68	36.30	106.00	82.50	63.50	81.50
3. P.C.	95.00	87.50	96.00	88.90	28.00	29.60	58.00	77.50	68.50	66.00
4. L.G.	103.25	102.50	127.00	124.90	30.43	31.90	87.00	78.50	78.00	57.00
5. S.N.	106.50	102.50	139.90	166.00	24.68	25.40	111.50	110.00	80.00	81.50
6. T.V.	112.50	107.50	128.00	132.50	42.96	39.50	117.50	147.50	95.00	102.50
MEAN	106.00	102.50	113.38	119.98	31.57	32.69	92.33	99.42	76.25	76.92
SEM	2.33	2.90	7.86	10.49	2.49	1.85	8.71	10.04	4.10	5.84
SD	5.70	7.11	19.25	25.71	6.10	4.53	21.33	24.59	10.04	14.30
ME	1.64		10.22		1.90		13.87		8.30	
CV (%)	1.57		8.76		5.92		14.47		10.84	
Pearson	r=0.96 (S)		r=0.83 (S)		r=0.91 (S)		r=0.64 (NS)		r=0.58 (NS)	
ANOVA	F=11.43 (S)		F=1.04 (NS)		F=0.87 (NS)		F=0.65 (NS)		F=0.02 (NS)	
	R=0.91 (S)		R=0.89 (S)		R=0.93 (S)		R=0.79 (S)		R=0.76 (S)	

trial reliability (Tables 10 and 11) gave similar results, the reliability ranging from high to very high ($0.88 < R < 0.98$; $4.44 < CV < 10.87$; $0.82 < r < 0.97$).

Peak Isokinetic Torque

For isokinetic peak torque, the day to day reliability was much lower than for the two previous measures of voluntary strength. The EF at $3.14 \cdot rad\ s^{-1}$ showed low to moderate reliability with insignificant correlation coefficients ($R = 0.66$ and $r = 0.45$) and a high coefficient of variation (16.18 %). For the three other isokinetic peak torque measurements (EF torque at 0.52 $rad \cdot s^{-1}$ and KE torque at both velocities of contraction), the reliability ranged from moderate to high ($0.74 < R < 0.79$; $10.84 < CV < 14.47$; $0.52 < r < 0.64$). Trial to trial reliability was higher than the day to day reliability ranging from high to very high ($0.87 < R < 0.95$; $5.35 < CV < 10.97$; $0.73 < r < 0.95$).

Contractile Properties

The day to day reliability for the contractile properties of the EF and KE muscles are presented in Tables 12 and 13, respectively. The intraclass correlation coefficient was negative for the EF time to peak torque (TPT). This was caused by a greater within subject variance than between subject variance. In other words, the TPT for the six subjects were similar (Baumgartner and Jackson,

Table 12. Trial to trial reliability of voluntary strength measurements of elbow flexor muscles, including elbow flexor maximum isometric torque at joint angles of 100° and 150°, and maximum isokinetic torque at velocities of contraction of 0.52 and 3.14 radian·second^{-1}. NS = non-significant. S = significant.

SUBJECTS	ISOM. 100 (N·m) TRIAL#1	TRIAL#2	ISOM. 150 (N·m) TRIAL#1	TRIAL#2	ISOK. 0.52 rad/s TRIAL#1	TRIAL#2	ISOK. 3.14 rad/s TRIAL#1	TRIAL#2
1. N.C.	23.53	22.61	16.41	16.49	20.00	24.00	16.00	18.00
2. M.D.	23.65	22.62	13.04	9.31	15.75	18.00	14.00	11.00
3. P.C.	18.20	17.26	10.17	10.09	16.50	12.00	14.00	13.00
4. L.G.	26.96	24.79	17.99	18.55	15.00	18.00	15.00	16.00
5. S.N.	30.17	32.57	23.41	19.98	20.00	21.00	14.50	18.25
6. T.V.	21.36	22.20	15.98	10.38	25.00	25.50	24.00	21.00
MEAN	23.98	23.68	16.17	14.13	18.71	19.75	16.25	16.21
SEM	1.56	1.87	1.68	1.77	1.40	1.82	1.44	1.37
SD	3.82	4.58	4.12	4.34	3.42	4.45	3.53	3.36
ME	1.06		1.65		1.94		1.78	
CV (%)	4.44		10.87		10.08		10.97	
Pearson	r=0.95 (S)		r=0.95 (S)		r=0.79 (S)		r=0.73 (S)	
ANOVA	F=0.21 (NS) R=0.97 (S)		F=3.81 (NS) R=0.88 (S)		F=0.72 (NS) R=0.87 (S)		F=0.001 (NS R=0.87 (S)	

Table 13. Trial to trial reliability of voluntary strength measurements of knee extensor muscles, including knee extensor maximum isometric torque at joint angles 90° and 160°, and maximum isokinetic torque at velocities of contraction of 0.52 and 3.14 radian·second^{-1}. NS = non-significant. S = significant.

SUBJECTS	ISOM. 90 (N·m) TRIAL#1	ISOM. 90 (N·m) TRIAL#2	ISOM. 160 (N·m) TRIAL#1	ISOM. 160 (N·m) TRIAL#2	ISOK. 0.52 rad/s TRIAL#1	ISOK. 0.52 rad/s TRIAL#2	ISOK. 3.14 rad/s TRIAL#1	ISOK. 3.14 rad/s TRIAL#2
1. N.C.	90.94	91.22	28.88	35.21	100.00	101.00	67.00	74.00
2. M.D.	109.11	117.12	34.09	36.03	82.50	85.00	79.00	84.00
3. P.C.	94.19	82.56	29.56	24.10	75.00	67.50	66.00	66.00
4. L.G.	124.05	120.67	30.12	30.46	81.00	76.00	57.00	56.00
5. S.N.	169.34	154.75	22.44	24.29	102.50	105.00	83.00	79.00
6. T.V.	133.51	128.43	38.54	40.41	102.00	120.00	95.00	85.00
MEAN	120.19	115.79	30.61	31.75	90.50	92.42	74.50	74.00
SEM	10.88	9.73	2.01	2.48	4.60	7.34	5.13	4.20
SD	26.65	23.84	4.93	6.07	11.26	17.97	12.57	10.28
ME	5.27		2.46		5.75		3.97	
CV (%)	4.47		7.90		6.29		5.35	
Pearson	r=0.96 (S)		r=0.82 (S)		r=0.95 (S)		r=0.90 (S)	
ANOVA	F=1.74 (NS) R=0.98 (S)		F=0.54 (NS) R=0.90 (S)		F=0.28 (NS) R=0.93 (S)		F=0.04 (NS) R=0.95 (S)	

Table 14. Day to day reliability of elbow flexor contractile properties, including twitch torque, time to peak torque, half-relaxation time, total contraction time, maximum rate of torque development and maximum rate of torque relaxation. NS = non -significant. S = significant.

SUBJECTS	TWITCH TORQUE (N·m) DAY#1	DAY#2	TIME TO PEAK TORQUE (ms) DAY#1	DAY#2	HALF-RELAXAT. TIME (ms) DAY#1	DAY#2	TOTAL CONTRAC. TIME (ms) DAY#1	DAY#2	MAX. RATE OF TORQUE DEVELOP. (N·m/ms) DAY#1	DAY#2	MAXIMUM RATE OF TORQUE RELAXATION (N·m/ms) DAY#1	DAY#2
1. N.C.	2.38	1.95	61.00	59.00	53.00	77.00	114.00	136.00	101.60	87.75	-36.9	-27.7
2. M.D.	2.52	2.01	71.00	59.00	72.00	94.00	143.00	153.00	110.90	78.50	-32.3	-27.7
3. P.C.	2.47	2.07	67.00	63.00	68.00	71.00	135.00	134.00	78.50	61.40	-32.3	-32.3
4. L.G.	3.78	2.77	63.00	63.00	73.00	69.00	136.00	132.00	106.20	106.20	-36.9	-46.2
5. S.N.	3.92	3.16	58.00	69.00	92.00	84.00	150.00	153.00	133.90	92.40	-46.2	-50.8
6. T.V.	2.41	1.79	60.00	62.00	80.00	92.00	140.00	154.00	97.00	97.00	-32.3	-27.7
MEAN	2.91	2.29	63.33	62.50	73.00	81.17	136.33	143.67	104.68	87.21	-36.15	-35.40
SEM	0.27	0.20	1.81	1.37	4.82	3.94	4.55	3.98	6.77	5.84	2.02	3.88
SD	0.67	0.50	4.42	3.35	11.80	9.65	11.15	9.74	16.58	14.29	4.94	9.50
ME	0.15		4.87		8.63		6.35		10.9		4.39	
CV (%)	5.75		7.74		11.19		4.53		11.36		-12.27	
Pearson	r=0.98 (S)		r=-0.56 (NS)		r=0.37 (NS)		r=0.64 (NS)		r=0.51 (NS)		r=0.81 (S)	
ANOVA	F=43.2 (S) R=0.73 (S)		F=0.07 (NS) R=-1.84		F=2.24 (NS) R=0.32 (NS)		F=3.34 (NS) R=0.69 (NS)		F=6.43 (NS) R=0.37 (NS)		F=0.07 (NS) R=0.83 (S)	

Table 15. Day to day reliability of knee extensor contractile properties, including twitch torque, time to peak torque, half-relaxation time, total contraction time, maximum rate of torque development and maximum rate of torque relaxation. NS = non-significant. S = significant.

UBJECTS	TWITCH TORQUE (N·m) DAY#1	TWITCH TORQUE (N·m) DAY#2	TIME TO PEAK TORQUE (ms) DAY#1	TIME TO PEAK TORQUE (ms) DAY#2	HALF-RELAXAT. TIME (ms) DAY#1	HALF-RELAXAT. TIME (ms) DAY#2	TOTAL CONTRAC. TIME (ms) DAY#1	TOTAL CONTRAC. TIME (ms) DAY#2	MAX. RATE OF TORQUE DEVELOP. (N·m/ms) DAY#1	MAX. RATE OF TORQUE DEVELOP. (N·m/ms) DAY#2	MAXIMUM RATE OF TORQUE RELAXATION (N·m/ms) DAY#1	MAXIMUM RATE OF TORQUE RELAXATION (N·m/ms) DAY#2
. N.C.	22.55	18.43	62.00	70.00	32.00	71.00	94.00	141.00	966.15	521.00	-596.75	-227.30
. M.D.	22.67	18.01	72.00	67.00	86.00	77.00	158.00	144.00	663.00	492.50	-369.40	-255.70
. P.C.	19.69	17.85	64.00	67.00	87.00	90.00	151.00	157.00	577.80	530.40	-265.20	-208.40
. L.G.	30.15	32.13	51.00	35.00	60.00	93.00	111.00	128.00	1496.50	1875.40	-464.10	-625.20
. S.N.	28.11	31.28	99.00	104.00	75.00	78.00	174.00	182.00	928.31	928.31	-274.70	-322.00
. T.V.	21.29	20.57	68.00	73.00	78.00	58.00	146.00	131.00	577.80	511.50	-227.30	-255.80
EAN	24.08	23.05	69.33	69.33	69.67	77.83	139.00	147.17	868.26	809.85	-366.24	-315.73
EM	1.53	2.53	6.03	8.17	7.78	4.77	11.29	7.43	131.10	204.17	52.87	58.30
D	3.75	6.19	14.76	20.02	19.05	11.68	27.65	18.20	321.13	500.11	129.50	142.80
E	2.05		5.80		15.03		14.78		172.50		117.75	
V (%)	8.68		8.37		20.38		10.33		20.56		-34.53	
earson	r=0.95 (S)		r=0.93 (S)		r=0.11 (NS)		r=0.66 (NS)		r=0.91 (S)		r=0.37 (NS)	
NOVA	F=0.64 (NS) R=0.92 (S)		F=0 (NS) R=0.95 (S)		F=0.74 (NS) R=0.21 (NS)		F=0.76 (NS) R=0.76 (S)		F=0.29 (NS) R=0.92 (S)		F=0.46 (NS) R=0.46 (S)	

1975). When using the CV from the ME a higher reliability was obtained with a value of 7.7 %.

The following measures for the EF, time to peak torque (TPT), total contraction time (TCT), half-relaxation time (HRT) and maximum rate of torque development (MRTD) had non-significant intra- and inter-class correlation coefficients. Similar results were found for the KE HRT and maximum rate of torque relaxation (MRTR). The coefficient of variation for these measures ranged from 4.53 % for the EF TCT to 34.53 % for the KE MRTR. Twitch torque (TT) for KE exhibited very high reliability. For the EF twitch torque a trend in the data was observed. Using the corrected formula for trend a R of 0.77 was found. With the second method, eliminating one subject (n=5) from the data, the second ANOVA had an even higher F value.

High to very high reliability was found for the EF MRTR (R = 0.83, CV = 12.27, r = 0.81) and for the KE TPT, TCT and MRTD ($0.76 < R < 0.95$, $8.37 < CV < 30.56$, $0.66 < r < 0.93$). While KE MRTR displayed a CV of 30.56 %, the R and r coefficients were over 0.90.

Trial to trial reliability for the contractile properties (Tables 14 and 15) was higher than the day to day reliability. Based on the intraclass correlation coefficient, the MRTD of the EF and MRTR of the KE gave coefficients that were insignificant, and CV of 11.7 and 39, respectively. The R of the EF TPT and TCT were

Table 16. Trial to trial reliability of elbow flexor contractile properties, including twitch torque, time to peak torque, half-relaxation time, total contraction time, maximum rate of torque development and maximum rate of torque relaxation. NS = non-significant. S = significant.

SUBJECT	TWITCH TORQUE (N·m) TRIAL#1	TWITCH TORQUE (N·m) TRIAL#2	TIME TO PEAK TORQUE (ms) TRIAL#1	TIME TO PEAK TORQUE (ms) TRIAL#2	HALF-RELAXAT. TIME (ms) TRIAL#1	HALF-RELAXAT. TIME (ms) TRIAL#2	TOTAL CONTRAC. TIME (ms) TRIAL#1	TOTAL CONTRAC. TIME (ms) TRIAL#2	MAX. RATE OF TORQUE DEVELOP. (N·m/ms) TRIAL#1	MAX. RATE OF TORQUE DEVELOP. (N·m/ms) TRIAL#2	MAXIMUM RATE OF TORQUE RELAXATIO (N·m/ms) TRIAL#1	MAXIMUM RATE OF TORQUE RELAXATIO (N·m/ms) TRIAL#2
1. N.C.	1.90	1.75	58.00	60.00	70.00	66.00	128.00	126.00	101.60	64.70	-18.5	-27.7
2. M.D.	1.98	2.03	50.00	54.00	94.00	94.00	144.00	148.00	73.90	83.10	-27.7	-27.7
3. P.C.	2.17	1.90	62.00	64.00	62.00	80.00	124.00	144.00	64.70	46.20	-27.7	-27.7
4. L.G.	2.67	2.86	52.00	62.00	70.00	68.00	122.00	130.00	101.60	92.40	-36.9	-46.2
5. S.N.	1.76	1.59	58.00	64.00	82.00	88.00	140.00	152.00	101.60	83.10	-55.4	-36.9
6. T.V.	1.76	1.59	54.00	62.00	88.00	96.00	142.00	158.00	101.60	92.40	-18.5	-27.7
MEAN	2.04	1.95	55.67	61.00	77.67	82.00	133.33	143.00	90.83	76.98	-30.78	-32.32
SEM	0.13	0.18	1.66	1.39	4.58	4.81	3.64	4.68	6.31	6.77	5.18	2.88
SD	0.31	0.44	4.07	3.42	11.22	11.78	8.92	11.47	15.46	16.58	12.68	7.06
ME	0.11		2.11		5.26		5.19		9.79		6.98	
CV (%)	5.54		3.61		6.58		3.76		11.66		-22.11	
Pearson	r=0.96 (S)		r=0.70 (S)		r=0.79 (S)		r=0.77 (S)		r=0.63 (NS)		r=0.63 (NS)	
ANOVA	F=1.54 (NS) R=0.95 (S)		F=16.0 (S) R=0.35 (NS)		F=1.70 (NS) R=0.87 (S)		F=8.67 (S) R=0.67 (NS)		F=5.01 (S) R=0.62 (NS)		F=0.12 (NS) R=0.74 (S)	

Table 17. Trial to trial reliability of knee extensor contractile properties, including twitch torque, time to peak torque, half-relaxation time, total contraction time, maximum rate of torque development and maximum rate of torque relaxation. NS = non-significant. S = significant.

SUBJECTS	TWITCH TORQUE (N·m) TRIAL#1	TWITCH TORQUE (N·m) TRIAL#2	TIME TO PEAK TORQUE (ms) TRIAL#1	TIME TO PEAK TORQUE (ms) TRIAL#2	HALF-RELAXAT. TIME (ms) TRIAL#1	HALF-RELAXAT. TIME (ms) TRIAL#2	TOTAL CONTRAC. TIME (ms) TRIAL#1	TOTAL CONTRAC. TIME (ms) TRIAL#2	MAX. RATE OF TORQUE DEVELOP. (N·m/ms) TRIAL#1	MAX. RATE OF TORQUE DEVELOP. (N·m/ms) TRIAL#2	MAXIMUM RATE OF TORQUE RELAXATION (N·m/ms) TRIAL#1	MAXIMUM RATE OF TORQUE RELAXATION (N·m/ms) TRIAL#2
1. N.C.	17.75	17.84	82.00	84.00	54.00	54.00	136.00	138.00	530.40	549.40	-284.20	-265.20
2. M.D.	17.78	18.00	76.00	78.00	64.00	66.00	140.00	144.00	511.50	492.50	-227.30	-246.30
3. P.C.	18.03	17.67	66.00	68.00	94.00	86.00	160.00	154.00	530.40	530.40	-189.40	-227.30
4. L.G.	29.31	34.95	40.00	38.00	104.00	96.00	144.00	134.00	1496.50	2254.30	-378.90	-871.40
5. S.N.	29.29	31.64	98.00	104.00	78.00	136.00	176.00	240.00	1041.90	966.10	-265.20	-322.00
6. T.V.	19.14	21.11	72.00	74.00	50.00	56.00	122.00	130.00	435.70	549.40	-246.30	-284.20
MEAN	21.88	23.54	72.33	74.33	74.00	82.33	146.33	156.67	757.73	890.35	-265.22	-369.40
SEM	2.15	2.88	7.17	8.07	8.15	11.60	7.09	15.53	157.61	257.47	24.05	92.45
SD	5.26	7.06	17.57	19.78	19.97	28.41	17.37	38.05	386.05	630.67	58.92	226.46
ME	1.44		1.63		16.11		17.5		201.72		123.13	
CV (%)	6.36		2.23		20.62		11.55		24.48		-39.06	
Pearson	r=0.99 (S)		r=0.999 (S)		r=0.61 (NS)		r=0.86 (S)		r=0.96 (S)		r=0.90 (S)	
ANOVA	F=3.27 (NS) R=0.96 (S)		F=3.75 (NS) R=0.99 (S)		F=0.67 (NS) R=0.74 (S)		F=0.87 (NS) R=0.79 (S)		F=1.08 (NS) R=0.92 (S)		F=1.77 (NS) R=0.56 (NS)	

significant after using the corrected formula for trend, yielding coefficients of 0.81 and 0.97 compared to 0.35 and 0.67 when using the unadjusted formula. When eliminating one subject (n=5) and conducting a second ANOVA, only the EF TCT gave a non-significant F and a R of 0.82. This second ANOVA, analysing the TPT, gaved a F value greater than the one obtained from the first analysis.

Reliability of TT measurements was very high for both limbs using all three of the statistical techniques to analyse the results. High to very high reliability was found for the rest of the other measurements consisting of the EF HRT, MRTR and of the KE HRT, TPT, TCT and MRTD.

DISCUSSION

The Method error of measurement used by Thorstensson in 1976, in a study measuring isokinetic peak torque, is the statistical technique typically used in studies addressing strength and related physiological parameters. In most cases, the coefficient of variation (CV) derived from this technique will be used to compare results of the present investigation with results from other reliability studies.

Strength Performance Measurements

Day to day reliability for the 1 RM performance measures were very high as displayed by the results from the three statistical techniques used. The day to day reliability of the bench press lift expressed by a r value (0.9) was in agrement with the result of Sailors and Berg (1982) for pubescent boys and adults. Reliability of the leg press lift (r = 0.96) in the present investigation was also very high, similar to the arm curl and squat results obtained by Sailors and Berg (1982).

Peak Isometric Torque

For voluntary isometric peak torque, both the day to day and trial to trial reliability were very high. This is reflected by the very high intraclass and interclass correlation coefficients. To the author's knowledge, no studies has examined the reliability of voluntary isometric peak torque for elbow flexion. For knee extension day to day reliability, the overall (combining the two joint angles) CV was 7.3 % which is similar to results obtained with adults ((Young et al., 1983; 1987, Desouza, 1987) and a mixed group of adults and children (Edwards et al., 1987) for the same measurements . The coefficient of variation for isometric peak torque for knee extension was similar to that for elbow flexion obtained in this study and thumb adduction (Sale, 1979; Edwards et al., 1987) and various other muscles (Friman, 1977).

The overall CV for the trial to trial reliability was 8 % and 6% for elbow flexion and knee extension, respectively. The trial to trial reliability for knee extension was slightly higher than the values found for adult subjects (Maughan et al., 1983) and a mix group of adult and children (Edwards et al., 1977).

Peak Isokinetic Torque

The day to day reliability for isokinetic peak torque measurements was the lowest of all three voluntary strength tests. Reliability was particularly low for the EF at the high velocity of contraction (3.14 $rad \cdot s^{-1}$) as reflected by the non-significant intraclass and interclass correlation coefficients (R=0.66 and r=0.45) and a CV of 16.2 %. The other three isokinetic measurements had high reliability based on the intraclass correlation coefficients. The overall CV (combining the two velocities of contraction) was 14.5 % for the EF and 12.7 % for the KE.

Many investigators have reported good reliability with the use of the Cybex dynamometer for knee extension in studies using adult subjects. Moffroid et al. (1969) and Lesmes et al. (1978) reported higher inter-class coefficients (Pearson product moment correlation coefficient : $r > 0.98$), than those observed in the present study, for day to day strength reliability. Lower CV's between 4.1 % and 6.5 % were also reported for the same joint by Thorstensson (1976). Sale (1979) found lower CV's at 0.52 $rad \cdot s^{-1}$ (5.9 %) and at 3.14 $rad \cdot s^{-1}$ (9.2 %), the two velocities of contraction, used to measure peak isometric torque in this experiment.

In the present study, two possibilities could explain the lower reliability obtained for EF torque at 3.14 rad s^{-1}. First, in relation to the KE, the lower reliability obtained for the EF could be attributed to differences in the stability of the particular joint during the testing. Because of the set-up for the measurement of isokinetic peak torque of the arm, it is more difficult to precisely align the elbow joint with the axis of rotation of the Cybex, than it is for the knee joint. Also because of it's smaller size, the arm could be more affected by the day to day variation in the positioning of the joint with the Cybex shaft.

Second, in relation to the lower velocity of contraction (0.52 $rad \cdot s^{-1}$), there are reports that reliability is lower for higher test velocity than for lower test velocity torque measurements (Vandervoort, 1982). This may be related to difficulties in recruiting the larger FT motor units and to a higher biological variation associated with this motor unit population (Vandervoort, 1982).

In comparison to other muscle groups, some studies have found higher or comparable day to day reliability. Using an inappropriate statistical technique (Pearson product moment correlation coefficient), a high reliability (r=0.98) was reported for the day to day reliability on an isokinetic leg press device using the Cybex dynamometer (Coyle et al., 1979) . A CV of 13.7 % was obtained with the same device by another investigator (Vandervoort, 1982). For elbow extension strength, CV's of 7.9 % (Sale, 1979) and between 8 to 15 % (Vandervoort et al., 1987) have been reported for day to day reliability. A CV of 15.5 % has also been reported for the day to day reliability of ankle plantar flexion (Sale, 1979).

The trial to trial reliability was very high based on the intra- and inter-class correlation coefficients. The overall CV was 10.5 for the EF and 5.8 for the KE. The greater reliability under these conditions is partly explained by the lower biological variation compared to the day to day situation. It may also be explained by a lower experimental error, since in this case the alignment of the joint articulation with the Cybex shaft was identical for the two trials. One study reports higher trial to trial reliability for elbow flexion with CVs between 2 % and 5 % (Vandervoort et al., 1987).

Again the greater CV for the EF may well be due to the experimental set-up. For the KE, a strap across the mid-upper thigh gave greater stability and hence less joint movement. For the EF, the arm wasfully extended on the table and stability was obtained only by exerting a downward pressure on the shoulder of the subject. Furthermore no adjustment of the seat was possible, so that the subjects' shoulder was sometimes higher than the table, making it difficult to eliminate lateral movement. Reliability for the EF could be improved by the use of a strap across the mid-upper arm and an adjustable "preacher" curl bench.

Contractile properties

Wide fluctuations for the contractile properties were observed for the day to day reliability. Surprisingly, the results from the trial to trial reliability which limits the error due to biological and methodological variations were similar to the day to day reliability.

To the author's knowledge no study has published results for the day to day reliability of contractile properties, in adults, for the muscle groups used in the present investigation. Twitch torque for both EF and KE showed high to very high reliability. Desouza (1987) (unpublished Master's dissertation) reported a CV of 8.7 % for knee extension twitch torque (TT) in adult subjects, a value very similar to the CV obtained in this investigation.

Variations in the value of CV's have been obtained for various muscle groups. Sale (1979) (unpublished doctoral's dissertation), reported the following values for

TT ; for the triceps surae, 5.6 %, the thenar, 11.5 %, the hypothenar 37.1 % and the extensor hallucius brevis, 11.3 %. Lambert (1975) studied the triceps surae and found a CV of 8 % for the same contractile property (TT). these results obtained in the present study for EF and KE TT were very similar to those reported for adults and show variability in day to day reliability from one muscle to another. For half-relaxation time (HRT), Sale (1979) found CV's of 12.1 %, 12 %, 15.2 % and 6.1 % for the extensor hallucius brevis, hypothenar, thenar and triceps surae muscle groups, respectively. The day to day reliability of HRT, in this study, could not be assessed by the intra- or inter-class reliability coefficients, because of the small number of subjects tested. However, the CV for EF HRT (11.2 %) was comparable to the CV's found by Sale for the four muscles discussed above, while the CV for KE (20.4 %) was higher.

A similar situation was found for time to peak torque (TPT), maximum rate of torque development (MRTD) and maximum rate of torque relaxation (MRTR). The intra- and inter-class coefficients could not provide information concerning the reliability of these contractile properties. The CV's for TPT of the EF and KE were in agreement with the values reported by Sale (1979) for the four muscles described above. Sale (1979) measured the rate of tension development (RTD) instead of the MRTD, and obtained a wide variability ranging from 8.7 % for the triceps surae to 30.9 % for the hypothenar. In this study the CV for the MRTD of the EF (11.4 %) was much lower than that of the KE (20.6 %). To the author's knowledge there are no published reports concerning the reliability of MRTR.

Sale (1979), combining the results for the four muscles described earlier, obtained CV's of 16.4 % for TT, 8 % for TCT, 18.1 % for RTD and 11.4 % for HRT. Combining results for EF and KE contractile properties in the present study, yielded the following results : 7.2 % for TT, 7.4 % for TCT, 16 % for MRTD and 15.8 % for HRT. For the trial to trial reliability, the same combined CV was 6.0 % for TT, 7.7 % for TCT, 18.1 % for MRTD and 27.1 % for HRT. While a direct comparison between prepubescent boys and adult males can only be drawn for the KE TT, it appears that contractile properties can be measured as reliably in children as in adults.

CONCLUSION

This study has examined two types of reliability of voluntary and evoked strength measures ; the day to day (stability) and trial to trial (test-retest on the same day) reliability. It has used three statistical techniques in order to assess the reliability of voluntary strength performance and contractile properties in pre-pubertal boys.

High reliability was obtained for all the strength measurements with the exception of the elbow flexor isokinetic torque. A recommendation was made regarding the set-up for this test, that should reduce the experimental error and hence increase reliability. The high level of motivation manifested by these young subjects demonstrate their capacity to perform maximal contractions. This was surely an important factor in decreasing the biological variation and consequently increasing reliability of the measurements in this study.

On the other hand, determination of the contractile properties is independent of voluntary control and should result in lower biological variation. While wide variations in the reliability of these contractile properties were observed, the results were in agreement with those obtained by Sale (1979) for an adult population. More studies are needed to determine if there are trends in the reliability of different muscles and contractile properties and if these are age and/or sex dependent.

Appendix B

Reliability and Accuracy of Computerized Axial Tomography

Techniques for the measurement of muscle cross-sectional area (CSA) have included anthropometry (Moritani and deVries, 1979), soft-tissue X-rays (Vrijens, 1978), ultrasonography (Ikai and Fukunaga, 1970) and computerized axial tomography (CAT) (Haggmark et al., 1978).

While a formula has been devised by Moritani and deVries (1980) to estimate lean muscle area using limb girth, circumferential skinfolds and skin thickness, anthropometric methods cannot distinguish between muscles and are considered unreliable (Young et al., 1983; Maughan, 1984). Furthermore, the use of this formula may result in large errors in the absolute magnitude of the measured lean cross-sectional area (Moritani and deVries), making it difficult to compare these results with those obtained using other methods.

Soft tissue X-rays, although being a reliable method for the measurement of fat thickness is not considered adequate for the determination of CSA (Haggmark et al., 1978; Hudash et al., 1983).

Ultrasonography is by far more accurate than the preceeding methods, however, it is difficult to obtain a highly defined CSA (Haggmark et al., 1978; Hudash et al., 1983). Differences in tissue density such as the one between fat and muscle, cause a reflection of high frequency sound wave s which may cause a certain degree of fuzziness around the periphery of the lean area, making it difficult to precisely assess muscle CSA (Haggmark et al., 1978).

Computerized axial tomography (CAT) is considered superior to ultrasonography, because it offers a higher image resolution, tissue specificity and interpretation (Ferruci, 1979). The higher resolution enables to some extent, a differentiation between muscle bellies composing a muscle. This allow the possibility to observe the effect of training on specific muscles. Another advantage is that CAT can display tissues of different density, such as fat and muscle, by assigning to each tissue an X-ray coefficient of attenuation (Maughan et al., 1983). This coefficient measures the degree of X-ray absorption by a tissue and is expressed in Hounsfield or EMI units depending on the type of scanner used (McCullough et al., 1977; Maughan et al., 1983).

The purposes of this study were to a) assess the reliability of CAT and b) to determine the accuracy of the technique. The accuracy represents " the closeness to the true value characteristic of such measurements " (Eisenhart, 1968, see Safrit, 1973). Accuracy is more closely associated with validity, while precision is used to describe reliability.

METHODS

i) Site to site reliability

Six adult females and five adult males were tested to assess the site to site reliability of computerized axial tomography (CAT). The right mid-upper arm of the subjects was marked between the acromion and the olecranon processes. The right mid-thigh was marked at the mid-distance between the pubic symphysis and the medial condyle of the femur. These two markings were referred to as the middle sites. Two points were marked one centimeter (cm) above and below the middle site and were referred to the proximal and distal sites. The arbitrary distance of one cm was chosen because it represented a generous estimate of the possible variability that could occur when marking the limb of a subject on two different occasions using anthropometric techniques. It is assumed that by choosing this distance, the site to site variability would also represent a liberal estimate of the day to day and trial to trial reliability of the CAT scan technique.

The arm and leg were scanned in a fully extended position. The proximal mark on the subject's limb was used to position the subjects on the table for the first scan. The table was then moved automatically toward the scanner by one cm for the second measurement. This procedure was repeated again for the third measurement.

Negative photographic slides of the CAT scan print were taken. These slides were projected on a piece of white paper and the bone, flexor, extensor and total lean area of the limbs were traced. The area measurements were determined by manual planimetry using a computerized digitizing platform (Sciptel corp., Columbus, Ohio). Each area was digitized three times and if the standard deviation of these three measurements was under 1 %, the mean was kept as the criterion score. The CAT scans were analysed in a double blind fashion, with the examiner being unaware of either the subject's name or the particurlar site scanned.

ii) Accuracy

Three settings are considered by the technician when using CAT for measurement of CSA ; the viewer controls, the reconstruction diameter and the thickness of the scanning beam. Other aspects that will affect a CAT scan , which will not be discussed here, include the noise (the spread of CT number around the mean value) in a scan, tissue noise, scan-to-scan variation and artifacts (McCullough, 1977).

The viewer controls include the window width and the window centre or level. The window width represents the range of x-ray absorption in an image and appears as a gray area. It is expressed by the CT number which is found by the following equation :

$$CT = \left[\frac{u - uw}{uw} \right] . a$$

where u and uw are the attenuation coefficients of the measured tissue and water, respectively, and a is a scaling factor chosen by the manufacturer (McCullough, 1977). The window centre is also expressed in CT numbers and represents the mid-value of the window width. The window setting will determine if an area is going to appear white, gray or black. For example, a window centre of 0 could have a window width of 200. This would mean that all areas over 100 CT numbers would appear white (e.g. bone), areas between -100 and 100 (muscle and fat) would be of a gray color and finally areas lower than -200 CT numbers (surrounding air) would appear black. Both window settings are determined by the technician during computer reconstruction of the image. The settings are defined using the wsu x command and are recalled using the win x command, this means that scans stored in memory can be called back and the settings can be modified.

The reconstruction diameter of the scan image is directly dependent upon the size of the limb that must be scanned. For example a diameter of 12.7 cm is too small to reconstruct the image of the cross-sectional area of the thigh of an adult male of average size. If the diameter is too big, the number of pixels in the measured area is sparse and image resolution is decreased.

Finally, the thickness of the beam will contribute to the accuracy of the technique. A thinner beam means that a thinner slice of CSA of the limb is scanned. The thickness of the beam is dependent on the image reconstruction diameter. At a diameter of 12.7 cm, a beam of less than 5 mm can be used. For diameters above 12.7 cm (25.4, 40.3 or 49.9 cm), the minimum thickness that can be used without affecting the clarity of the image is 5 mm.

On one hand , window width, image reconstruction diameter and beam thickness can easily be determined by the technician and have only a small impact on the accuracy of the image. On the other hand, an optimal window center or level is harder to obtain and the chosen level may affect the resolution and size of the CSA (Koehler et al., 1979).

In order to determine the accuracy of CAT, solid circular phantoms of a known diameter were scanned (Model 20-30, Ohio Nuclear) and digitized though manual planimetry using a computerized digitizing platform (Scriptel corp., Columbus, Ohio) and a software program (Sigma-scan, Jandel Scientific, 1986). The phantoms are circular plexiglass cylinders with a known area, filled with water. There are four phantoms, one for each diameter of image reconstruction (radius 5.75 cm, 11.45 cm, 17.75 cm and 22.75 cm). They are used to periodically calibrate the scanner by adjusting the window centre to a CT number of 0, which is given by convention to water.

The actual area of these phantoms was determined by measuring their diameter and calculating their area using the formula πr^2. The phantoms were scanned, photographed, traced and digitized using the procedure outlined earlier, for the cross-sectional area of limbs. The actual area was compared with the digitized area. A regression equation was derived using the actual and digitized areas and the actual areas were predicted using this equation.

STATISTICS

i) Site to site reliability

Statistical analysis was conducted for the arm bone, flexor and total lean area and for the leg bone, extensor area and total lean area. Two-way analyses of variance with one repeated measure were used for each of these six areas in order to determine if there was a sex difference (between factor) and a difference within subjects between the 3 sites (repeated or within factor). Reliability of the site measurements was determined by comparing adjacent sites. It was estimated using Pearson product-moment correlation (interclass correlation coefficient), one-way Analysis of variance (intraclass correlation coefficient) and the Method error of measurement described in appendix A. The intraclass correlation coefficient was estimated by considering day to day or trial to trial variance as part of the measurement error.

ii) Accuracy

A regression equation was predicted from the actual and digitized areas of the phantoms. A two way analysis of variance with one repeated measure was conducted to determine if there was any significant difference between the digitized, actual and predicted areas of the phantoms. One way analysis of variance (intraclass correlation coefficient), Pearson product-moment correlation (interclass correlation coefficient) and the Method error of measurements were also calculated to give the reliability of these measurements.

RESULTS

i) Site to site reliability

No differences were found between males and females for the site position on any of the six area measurements (Tables 18 to 23). Differences were found between the proximal and distal sites for all measurements except for the bone area of the leg (Table 21). Differences were also found between the proximal and middle sites for the elbow

Tables 18 to 23. Analysis of variance summary tables for position site of marking for computerized axial tomography.

Table 18. Arm bone cross-sectional area (cm^2).
Table 19. Elbow flexor cross-sectional area (cm^2).
Table 20. Lean arm cross-sectional area (cm^2).
Table 21. Leg bone cross-sectional area (cm^2).
Table 22. Knee extensor cross-sectional area (cm^2).
Table 23. Lean leg cross-sectional area (cm^2).

Abbreviations for Anova tables :
SS : Sums of squares
DF : Degrees of freedom
MS : Mean square
F : F value
NS : Non-significant
* : Significant (.05)
** : Significant (.01)

Table 18. Summary of analysis of variance for site position for arm bone cross-sectional area.

Two-way anova with repeated measures on one variable

Source	SS	DF	MS	F
Between				
Sex	24.06	1	24.06	31 **
Error	6.99	9	0.78	
Within				
Site	0.66	2	0.33	6.82 **
Sex x site	0.30	2	0.15	3.08 NS
Error	0.87	18	4.9-02	

Table 19. Summary of analysis of variance for site position for elbow flexor cross-sectional area.

Two-way anova with repeated measures on one variable

Source	SS	DF	MS	F
Between				
Sex	1016.43	1	1016.43	22.64 **
Error	404.04	9	44.89	
Within				
Site	30.3	2	15.15	5.61 *
Sex x site	11.38	2	5.69	2.11 NS
Error	48.61	18	2.7	

Table 20. Summary of analysis of variance for site position for lean arm cross-sectional area.

Two-way anova with repeated measures on one variable

Source	SS	DF	MS	F
Between				
Sex	6439.29	1	6439.29	30.31 **
Error	1487.08	7	212.44	
Within				
Site	56.42	2	28.21	5.80 *
Sex x site	2.53	2	1.26	0.26 NS
Error	68.25	14	4.88	

Table 21. Summary of analysis of variance for site position for leg bone cross-sectional area.

Two-way anova with repeated measures on one variable

Source	SS	DF	MS	F
Between				
Sex	14.95	1	14.95	10.31 **
Error	10.14	8	1.45	
Within				
Site	1.10	2	0.55	3.16 NS
Sex x site	0.22	2	0.11	0.62 NS
Error	2.45	14	0.17	

Table 22. Summary of analysis of variance for site position for knee extensor cross-sectional area.

Two-way anova with repeated measures on one variable

Source	SS	DF	MS	F
Between				
Sex	5242.26	1	5242.26	16.9 **
Error	2171.09	7	310.16	
Within				
Site	76.50	2	38.25	8.80 **
Sex x site	7.65	2	3.82	0.88 NS
Error	60.83	14	4.34	

Table 23. Summary of analysis of variance for site position for lean leg cross-sectional area.

Two-way anova with repeated measures on one variable

Source	SS	DF	MS	F
Between				
Sex	18983.2	1	18983.2	28.08 **
Error	4732.56	7	676.08	
Within				
Site	235.21	2	117.60	5.09 *
Sex x site	3.13	2	1.56	6.76-02
Error	323.31	14	23.09	

flexor area and the lean arm area (Tables 18 and 19). Finally a difference between the middle and distal sites was found for the knee extensor area (Table 21). The results for the site to site differences in CSA are summarized in figure 16.

Reliability (Tables 24 to 29) using all three statistical techniques was very high between the three sites for all six measurements ($0.86 < R < 0.99$, $2.4 < CV\ \% < 12.3$, $0.81 < r < 0.99$).

ii) Accuracy

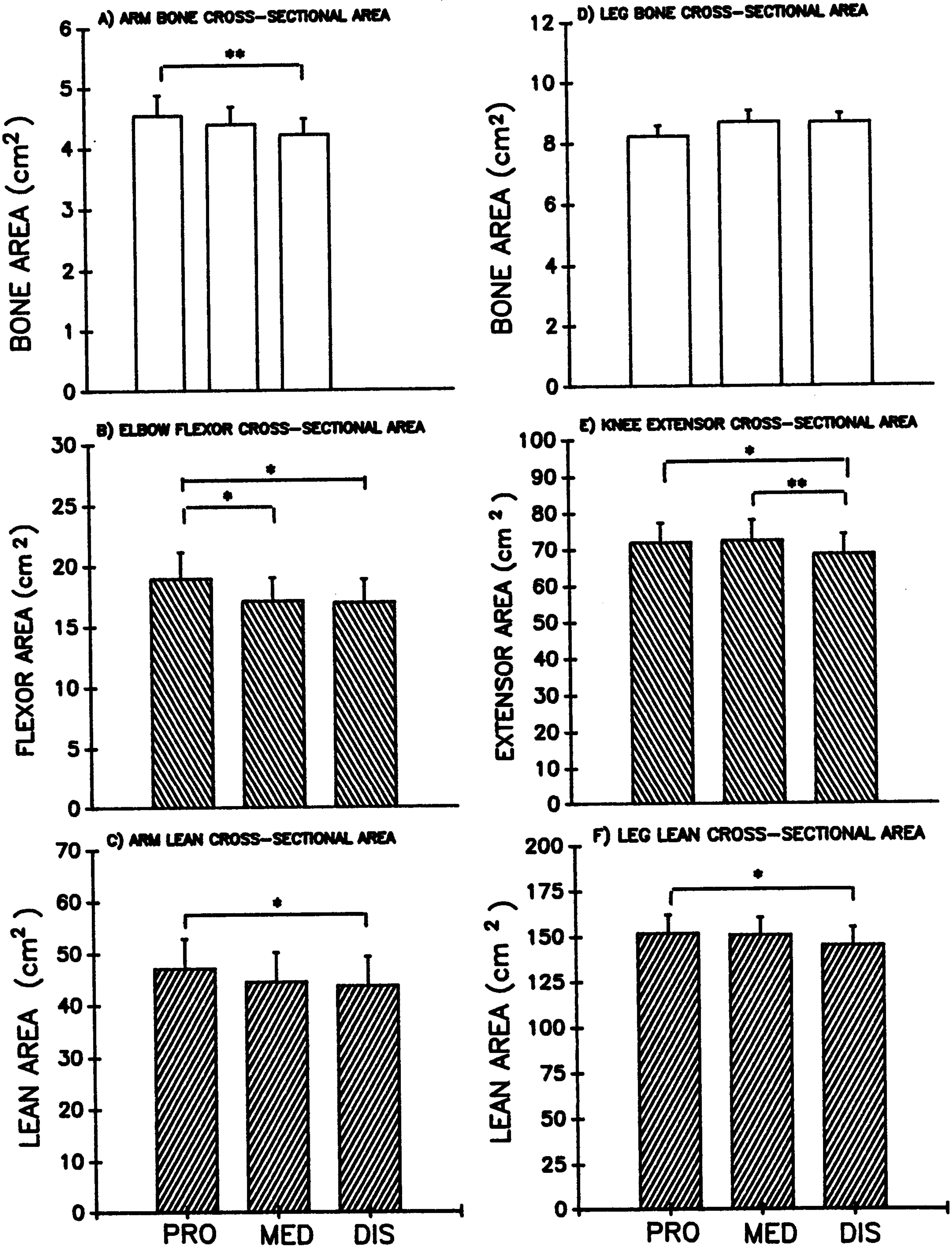
No differences were found between the digitized, actual or predicted areas of the phantoms (Table 30 and figure 17). Reliability of these measurements was very high ($0.99 < R < 0.999$, $1.28 < CV\ \% < 3.94$, $0.99 < r < 0.99$).

DISCUSSION

i) Site to site reliability

While differences between the proximal and distal sites were found for most of the areas measured, it is unlikely that the marking of a site on two occasions would vary by 2 centimeters (cm). With a 1 cm difference in site (proximal-middle or middle-distal) a difference was found in 25 % of the cases. The arm displayed greater variation when moving proximally up the limb. For the leg and more specifically the quadriceps (knee extensors) greater variability was found when moving toward the distal end of

Figure 16. Differences in cross-sectional area for proximal, middle and distal sites for A) arm bone cross-sectional area, B) arm flexor cross-sectional area, C) arm lean cross-sectional area, D) leg bone cross-sectional area, E) leg extensor cross-sectional area and F) leg lean cross-sectional area. Values are means ± SEM. Significant site differences * $p < .05$; ** $p < .01$.


A) ARM BONE CROSS-SECTIONAL AREA
BONE AREA (cm²)
D) LEG BONE CROSS-SECTIONAL AREA
BONE AREA (cm²)
B) ELBOW FLEXOR CROSS-SECTIONAL AREA
FLEXOR AREA (cm²)
E) KNEE EXTENSOR CROSS-SECTIONAL AREA
EXTENSOR AREA (cm²)
C) ARM LEAN CROSS-SECTIONAL AREA
LEAN AREA (cm²)
F) LEG LEAN CROSS-SECTIONAL AREA
LEAN AREA (cm²)
PRO
MED
DIS
PRO
MED
DIS

Tables 24 to 29. Site to site reliability of computerized axial tomography. Data are cross-sectional area in cm^2.

Table 24. Arm bone cross-sectional area (cm^2).
Table 25. Elbow flexor cross-sectional area (cm^2).
Table 26. Lean arm cross-sectional area (cm^2).
Table 27. Leg bone cross-sectional area (cm^2).
Table 28. Knee extensor cross-sectional area (cm^2).
Table 29. Lean leg cross-sectional area (cm^2).

Abbreviations for sites : PRO : proximal
MID : middle
DIS : distal

Table 24. Site to site reliability of arm bone cross-sectional area

SUBJECTS	PRO	MID	MID	DIS	PRO	DIS
S.F.	3.31	3.42	3.42	3.00	3.31	3.00
J.M.	3.05	3.23	3.23	3.26	3.05	3.26
D.S.	3.52	3.37	3.37	3.58	3.52	3.58
T.F.	3.00	3.29	3.29	3.18	3.00	3.18
J.C.	4.70	3.93	3.93	4.01	4.70	4.01
K.S.	4.34	4.40	4.40	4.22	4.34	4.22
D.C.	5.97	5.68	5.68	5.84	5.97	5.84
A.B.	5.60	5.16	5.16	4.53	5.60	4.53
M.M.	4.76	4.61	4.61	4.42	4.76	4.42
J.R.	5.86	5.46	5.46	5.09	5.86	5.09
D.H.	5.80	5.73	5.73	5.21	5.80	5.21
MEAN	4.54	4.39	4.39	4.21	4.54	4.21
SEM	0.34	0.29	0.29	0.26	0.34	0.26
SD	1.12	0.95	0.95	0.88	1.12	0.88
ME	0.21		0.19		0.28	
CV (%)	4.7		4.4		6.4	
Pearson	r=0.97 (S)		r=0.96 (S)		r=0.95 (S)	
ANOVA	F=2.5 (NS) R=0.57 (NS)		F=4.3 (NS) R=0.97 (S)		F=0.67 (S) R=0.94 (S)	

Table 25. Site to site reliability of elbow flexor cross-sectional area.

SUBJECTS	PRO	MID	MID	DIS	PRO	DIS
S.F.	11.39	9.11	9.11	9.03	11.39	9.03
J.M.	13.09	12.03	12.03	9.96	13.09	9.96
D.S.	12.85	14.87	14.87	16.87	12.85	16.87
T.F.	13.64	11.11	11.11	8.78	13.64	8.78
J.C.	14.91	12.15	12.15	13.73	14.91	13.73
K.S.	12.93	14.65	14.65	15.77	12.93	15.77
D.C.	20.71	16.65	16.65	16.82	20.71	16.82
A.B.	25.34	23.50	23.50	25.86	25.34	25.86
M.M.	24.00	21.37	21.37	19.05	24.00	19.05
J.R.	23.98	21.07	21.07	21.07	23.98	21.07
D.H.	35.64	31.68	31.68	29.53	35.64	29.53
MEAN	18.95	17.11	17.11	16.95	18.95	16.95
SEM	2.19	1.93	1.93	1.93	2.19	1.93
SD	7.28	6.39	6.39	6.39	7.28	6.39
ME	1.36		1.22		2.2	
CV (%)	7.6		7.2		12.3	
Pearson	r=0.97 (S)		r=0.96 (S)		r=0.90 (S)	
ANOVA	F=9.1 (S)		F=0.8 (NS)		F=4.1 (NS)	
	R=0.96 (S)		R=0.98 (S)		R=0.93 (S)	

Table 26. Site to site reliability of lean arm cross-sectional area.

SUBJECTS	PRO	MID	MID	DIS	PRO	DIS
S.F.	31.17	29.08	29.08	26.58	31.17	26.58
J.M.	29.70	30.62	30.62	28.38	29.70	28.38
D.S.	40.76	34.23	34.23	42.96	40.76	42.96
T.F.	32.97	31.79	31.79	28.10	32.97	28.10
K.C.	34.19	32.46	32.46	29.35	34.19	29.35
J.C.	47.10	41.93	41.93	42.62	47.10	42.62
A.B.	68.80	64.78	64.78	62.31	68.80	62.31
M.M.	57.50	54.47	54.47	53.79	57.50	53.79
J.R.	81.17	80.58	80.58	78.42	81.17	78.42
MEAN	47.04	44.44	44.44	43.61	47.04	43.61
SEM	5.78	5.73	5.73	5.70	5.78	5.70
SD	17.33	17.20	17.20	17.10	17.33	17.10
ME	1.56		2.54		1.71	
CV (%)	3.4		5.8		3.8	
Pearson	r=0.99 (S)		r=0.98 (S)		r=0.98 (S)	
ANOVA	F=11.2 (S) R=0.99 (S)		F=0.4 (NS) R=0.99 (S)		F=16.1 (S) R=0.99 (S)	

Table 27. Site to site reliability of leg bone cross-sectional area.

SUBJECTS	PRO	MID	MID	DIS	PRO	DIS
S.F	7.16	7.84	7.84	6.98	7.16	6.98
K.C.	8.74	9.92	9.92	9.22	8.74	9.22
D.S.	7.27	7.59	7.59	8.29	7.27	8.29
J.M.	6.56	6.90	6.90	8.29	6.56	8.29
J.C.	7.66	7.67	7.67	7.73	7.66	7.73
D.C.	9.73	10.19	10.19	10.10	9.73	10.10
J.R.	9.05	9.51	9.51	9.23	9.05	9.23
M.M.	8.58	9.24	9.24	9.10	8.58	9.10
D.H.	9.28	9.25	9.25	8.99	9.28	8.99
MEAN	8.22	8.68	8.68	8.66	8.22	8.66
SEM	0.34	0.37	0.37	0.29	0.34	0.29
SD	1.03	1.12	1.12	0.88	1.03	0.88
ME	0.25		0.46		0.42	
CV (%)	4.1		7.7		7.0	
Pearson	r=0.95 (S)		r=0.81 (S)		r=0.82 (S)	
ANOVA	F=13.9 (S) R=0.94 (S)		F=0.009 (NS) R=0.9 (S)		F=4.4 (S) R=0.86 (S)	

Table 28. Site to site reliability of knee extensor cross-sectional area.

SUBJECTS	PRO	MID	MID	DIS	PRO	DIS
S.F	61.48	59.93	59.93	53.54	61.48	53.54
K.C.	48.95	53.27	53.27	45.66	48.95	45.66
D.S.	64.77	63.55	63.55	62.70	64.77	62.70
J.M.	56.58	55.37	55.37	53.27	56.58	53.27
J.C.	68.42	64.93	64.93	65.08	68.42	65.08
D.C.	69.57	69.98	69.98	67.96	69.57	67.96
J.R.	99.94	99.45	99.45	97.33	99.94	97.33
M.M.	81.12	85.79	85.79	81.86	81.12	81.86
D.H.	96.12	99.45	99.45	89.92	96.12	89.92
MEAN	71.88	72.41	72.41	68.59	71.88	68.59
SEM	5.44	5.66	5.66	5.55	5.44	5.55
SD	16.32	16.98	16.98	16.64	16.32	16.64
ME	1.93		2.2		1.68	
CV (%)	2.7		3.1		2.4	
Pearson	r=0.99 (S)		r=0.98 (S)		r=0.99 (S)	
ANOVA	F=0.3 (NS) R=0.99 (S)		F=12.1 (S) R=0.98 (S)		F=15.3 (S) R=0.99 (S)	

Table 29. Site to site reliability of lean leg cross-sectional area.

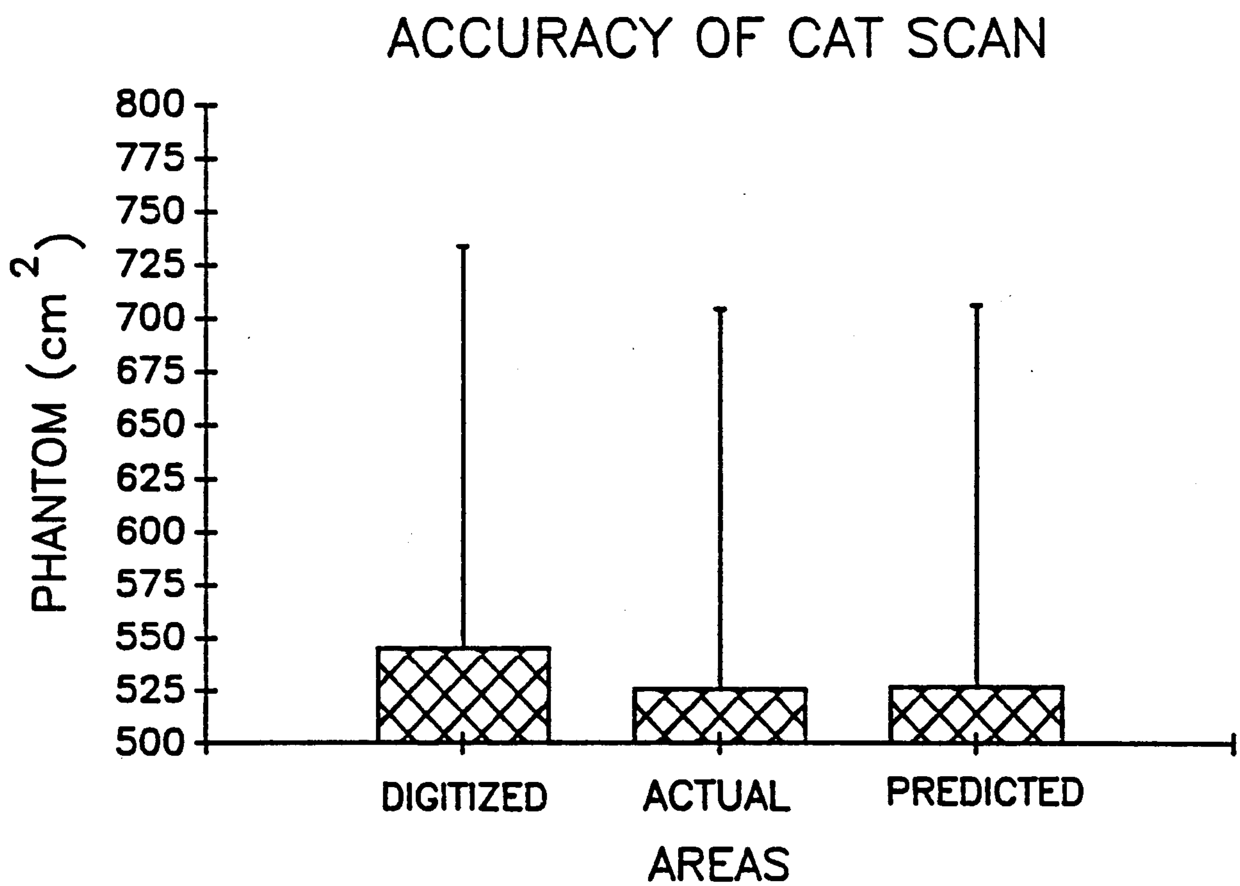
SUBJECTS	PRO	MID	MID	DIS	PRO	DIS
S.F	126.15	126.22	126.22	114.14	126.15	114.14
K.S.	113.93	123.35	123.35	107.68	113.93	107.68
D.S.	137.56	136.49	136.49	138.88	137.56	138.88
J.M.	122.25	119.30	119.30	116.52	122.25	116.52
J.C.	139.01	132.56	132.56	129.80	139.01	129.80
D.C.	155.39	151.88	151.88	145.74	155.39	145.74
J.R.	201.53	197.16	197.16	187.90	201.53	187.90
M.M.	173.11	184.41	184.41	177.24	173.11	177.24
D.H.	197.75	186.90	186.90	188.40	197.75	188.40
MEAN	151.85	150.92	150.92	145.14	151.85	145.14
SEM	10.17	9.60	9.60	10.05	10.17	10.05
SD	30.52	28.81	28.81	30.16	30.52	30.16
ME	4.8		4.0		4.0	
CV (%)	3.1		2.7		2.7	
Pearson	r=0.98 (S)		r=0.98 (S)		r=0.98 (S)	
ANOVA	F=0.2 (NS) R=0.99 (S)		F=8.3 (S) R=0.98 (S)		F=11.6 (S) R=0.98 (S)	

Table 30. Accuracy of computerized axial tomography ; comparison of actual, digitized and predicted cross-sectional area of phantoms. Table includes : image recontruction diameters, actual diameter of phantom, actual distance between cross-hairs derived from the scans, tracing distance between the cross-hairs, conversion factor to transform actual area to tracing area, digitized area, actual area and predicted area from regression equation. NS = non-significant and S = significant.

Image reconstruction diameter (cm)	Diameter of phantom (cm)	Actual distance between cross-hairs (cm)	Tracing distance between cross-hairs (cm)	Conversion factor actual to tracing area	Digitized area (cm2)	Digitized converted area (cm2)	Actual area (cm2)	Actual area (cm2)	Predicted area from regression equation (cm2)	Digitized converted area (cm2)	Predicted area from regression equation (cm2)
12.70 (#1)	11.50	11.10	26.00	5.50	561.75	102.14	103.87	103.87	106.24	102.39	106.24
12.70 (#2)	11.50	11.10	26.20	5.57	569.32	102.19	103.87	103.87	106.05	102.19	106.05
12.70 (#3)	11.50	11.00	26.20	5.67	569.41	100.37	103.87	103.87	104.33	100.37	104.33
25.40 (#1)	22.90	22.80	26.90	1.39	587.42	422.00	419.10	419.10	409.07	422.00	409.07
25.40 (#2)	22.90	23.00	27.00	1.38	591.13	428.95	419.10	419.10	415.65	428.95	415.65
25.40 (#3)	22.90	23.00	27.00	1.38	588.74	427.21	419.10	419.10	414.01	427.21	414.01
40.30	35.50	36.00	26.20	0.53	561.72	1060.44	989.80	989.80	1013.99	1060.44	1013.99
49.90	45.50	46.00	27.50	0.36	613.94	1717.80	1647.48	1647.48	1645.58	1717.80	1645.58
MEAN						545.14	525.77	525.77	526.86	545.17	526.86
SEM						188.48	178.61	178.61	179.42	188.47	179.42
SD						533.09	505.19	505.19	507.49	533.07	507.49
ME						21.09		6.75		18.13	
V %						3.94		1.28		3.38	
Pearson						r=0.99 (S)		r=0.99 (S)		r=0.99 (S)	
ANOVA						F=2.96 (NS) R=0.999 (S)		F=0.09 (NS) R=0.999 (S)		F=3.56 (NS) R=0.999 (S)	

Regression equation : predicted area = 0.9474972 x digitized area + 9.22753

Figure 17. Accuracy of computerized axial tomography. Comparison of digitized, actual and predicted phantom area. Values are means ± SEM.


ACCURACY OF CAT SCAN
800
775
750
725
700
675
650
625
600
575
550
525
500
PHANTOM (cm 2)
DIGITIZED
ACTUAL
PREDICTED
AREAS

the limb.

As was mentioned in the method section, a 1 cm difference was considered a liberal estimate of the variability of site marking on two occasions. The highest beam thickness used for scanning the cross-sectional area was 0.5 cm. The slice of cross-sectional area that is reconstructed by the computer uses the average density in that 0.5 cm scanned slice. This means that two sites separated by 1 cm are separated by only about 0.5 cm when the thickness of the beam is taken into account.

In longitudinal studies dealing with children, growth of body segments is an important consideration when taking anthropometric or CAT measurements. In the present investigation, the same criteria were used for pre and post measurements. This assumed uniform growth of entire segments in proportion to overall growth in stature. Segment length was not assessed in this study, but body height which is known to be highly correlated with segment length showed no change.

One possible way to increase the reliability of CAT technique is to perform a scout scan of the entire limb, identifying the proximal and distal boundaries and scanning the mid-point between these two extremeties. Again reliability will depend on how accurately the arm is positioned and wheter the technician can identify the limb boundaries on the second occasion. One advantage is that the technician can store this first scan and recall it before doing the second measurements.

One practical recommendation, that should improve reliability would be the use of foam blocks to support the arm and legs of the subject during the scanning procedure. This would ensure that the limb, at the predetermined site for scanning, is not compressed by it's own weight on the table and that the limb position at pre- and post-testing is similar. When a limb is compressed, it becomes more difficult to identify and separate individual muscle groups from the scan for area tracing. Consequently the risk of making a mistake in tracing these areas is increased.

The identification of specific muscle bellies of the lean CSA remains the biggest challenge for the use of CAT technology in the determination of muscle hypertrophy. Like Hudash et al. (1985), who used a similar scanner (Fourth Generation) , the author of the present study often found it difficult to separate the extensor and flexor muscle groups. Cureton et al. (1988) decided not to measure the flexor and extensor muscles of arm and leg, of adult males and females, because they could not be precisely determined in some of the scans. Hudash et al. (1985) could not separate the specific muscles of the hamstrings in football players with a body fat level of less than 20 %, but the gracilis and sartorius appeared reasonably well defined in players with more than 8 % body fat. Gracilis and sartorius could also be idendified and traced with facility in the present investigation.

In contrast, Haggmark et al. (1978) reported that CAT offers an accurate way of measuring the size of various muscle bellies, such as the musculus vastus lateralis (vastus lateralis and intermedius). While Haggmark et al. (1978) found a CV of 2.4 %, they estimated reliability of CAT, from measurements of the CSA of phantoms. Reliability might have been quite different, if the authors had used single muscle bellies. Determination of the CSA of a specific muscle group is important, when trying to assess the effect of a particurlar exercise on this muscle group. Since CSA of the total muscle is easier to determine, one possible way to obviate the problem of identifying single muscle bellies, is to train and measure the torque produced by both extensor and flexor muscles and divide by the total lean CSA. This would provide a ratio, that could be valuable indicator of muscular adaptations to training.

Studies have reported a high reliability for CAT measurements of limb CSA. Maughan et al. (1983) obtained a coefficient of variation of 1.6 % after making duplicate measurements of ten legs. Hudash et al. (1985) made duplicate measurements of the CSA areas of the mid-thigh bone, fat, lean and total CSA. Only the muscle lean CSA was significantly different. Cureton et al. (1988) measured trial to trial reliability by scanning the leg and arm of

12 subjects twice. They found an intraclass coefficient of 0.99 for both limbs. Again no attempt was made to determine the reliability of single muscle belly.

ii) Accuracy of the CAT Scan technique

When the negative prints of the phantom scans were processed, it was noticed that the CSA was elongated from bottom to top giving an ellipsoidal form to the phantom image. The lens used in the photography of the computerized reconstructed image was responsible for the deformation. It caused distortion on the upper and bottom parts of the negative. This affected the determination of the CSA of the phantoms more than that of the limbs, since the phantoms comprised a larger fraction of the total viewing area than did the limbs.

The limbs because of their smaller CSA were positioned in the middle of the screen and consequently were generally not affected by the distortion. In a few cases, limbs were affected by the distortion because the technician had selected a diameter of image reconstruction which was too small for the CSA of the limb. In these cases, the technician was asked to recall the scan from the computer memory and to reproduce the image using a more suitable diameter of image reconstruction.

Despite the distortion effect the digitized CSA was not significantly different from the actual area of the phantom. The magnitude of the difference between digitized and actual CSA of phantoms of diverse sizes (11.5 and 45.8 cm of diameter) varied from -1.5 to 70.3 cm^2 (Table 30). Nevertheless, this suggests that to avoid the distortion effect, the diameter of image reconstruction should be sufficienly high, to ensure that the scanned limb is totally centered in the middle of the screen.

While this study did not examine the effect of varying window center on the resolution or size of the CSA of the phantom, blurring of sharp edges described by Koehler et al. (1979) were visible on some scans. Although this blurring of the edges makes the determination of the periphery difficult, the extent of it's effect on the size of the CSA, measured during this study, remains to be determined.

Koehler et al. (1979) showed that the diameter of phantoms could vary by 8 to 10 mm by varying the window center control. The implication of this variation in diameter and consequently CSA are serious in training studies, such as the present investigation, were pre-and post-measurements are made. Table 31 shows the pre- and post-window center settings for the arm scan of 15 prepubertal boys. There was a significant difference between the pre- and post-setting measurements. Cureton et al. (1988) estimated that the error, due to a shift in

Table 31. Reliability of CAT window settings (width and centre) and of arm bone CSA in prepubescent boys before and after a 20 week time period.

Table 31. Reliability of CAT window settings and arm bone CSA in prepubescent boys before and after a 20 week time-period.

SUBJECTS	PRE WIND. WIDTH	POST WIND. WIDTH	PRE WIND. CENTRE	POST WIND. CENTRE	PRE BONE AREA	POST BONE AREA
G.J.	1024	651	125	-93	2.75	2.66
D.R.	714	670	-240	-110	3.00	2.82
G.G.	980	719	107	-112	2.09	2.12
L.G.	1462	636	122	-74	2.66	2.74
N.C.	774	645	58	-207	3.10	2.91
M.W.	763	582	65	-124	2.90	2.68
I.O.	730	680	-243	-97	3.12	2.91
P.C.	1701	704	115	-112	2.48	2.61
M.F.	950	702	48	-74	2.37	1.83
M.H.	585	612	-268	-138	2.92	2.88
T.K.	635	582	-257	-124	2.45	2.62
A.M.	828	632	-21	-83	2.53	2.46
S.G.	1246	494	102	-259	2.78	2.86
S.N.	1101	481	107	-226	3.37	3.18
T.K.	815	629	50	-65	2.71	2.39
MEAN	953.87	627.93	-8.67	-126.53	2.75	2.64
SEM	78.27	17.51	39.06	14.60	0.08	0.08
SD	303.13	67.80	151.28	56.54	0.32	0.33
ME		218.5		119.6		0.1
V %		55.3		-176.9		4.8
Pearson		r=0.03 (NS)		r=-0.15 (NS)		r=0.84 (S)
ANOVA		F=15.6 (S)		F=6.8 (S)		F=4.5 (NS)

window centre and width from pre- to post-measurements of muscle and fat CSA of the arm and leg was 3.5 %. A possible way to eliminate the differrence would be to record the pre-setting and use a similar setting for post-measurements.

CONCLUSION

While CAT techniques appears to be highly reliable (Haggmark et al., 1978; Cureton et al., 1988) and offer the best resolution among methods for measuring cross-sectional area (Maughan, 1984b), the method is questionable when attempting quantitative measurements of specific muscle bellies. Refinements in CAT technology are necessary to increase image resolution and facilitate precise differentiation of specific muscle bellies.

Increased resolution has already been achieved with a new generation of scanners that can create new pixels in an image, based on the average CT number of a few pixels in that area. The impact of these new scanners on the determination of CSA of muscles remains to be determined. Another improvement that would eliminate the methodological error and reduce the amount of work associated with the determination of CSA,is computerized reading of specific areas based on a range of tissue density, pre-determined by the technician.

Finally technology such as nuclear magnetic resonance may provide a more accurate mean of measuring CSA in the near future, without the risk of exposure to ionizing radiation.

Appendix C

Intertester reliability of digitizing procedure used to assess muscle cross-sectional area from computerized axial tomography.

Guidelines for the tracing of the photographic negative slides to paper were established before the beginning of the study. These were critical, especially for the partition of the muscles into extensor and flexor groups, which was not always apparent from the scan image.

Intertester reliability or objectivity was examined for the digitizing of tracings used to determine bone and muscle cross-sectional area.

METHODS

Tracings of the limbs of six subjects were used to determine the objectivity of the digittizing technique. Digitizing was done by manual planimetry using a computerized digitizing platform (Scriptel Corp., Columbus, Ohio) and a software program (Sigma-scan, Jandel Scientific, 1986). The bone and total areas of these limbs were digitized independently by two observers with similar training without any knowledge of the subject's identity. Results from the independent assessments were subsequently analysed using the following statistical procedures.

STATISTICS

Objectivity was estimated using the Pearson product-moment correlation (interclass correlation coefficient), Analysis of variance (intraclass correlation coefficient) and the Method error of measurements, all described in appendix A.

RESULTS

Interobserver reliability was very high for both bone and total area as reflected by high intra (R = 0.98 and 0.99) and interclass (r= 0.97 and 0.98) correlation coefficients and low coefficients of variation (CV = 1.61 % and 1.11 %). No significant difference was found between two observers digitizing the same thigh bone and total area (Table 32 and Figure 18).

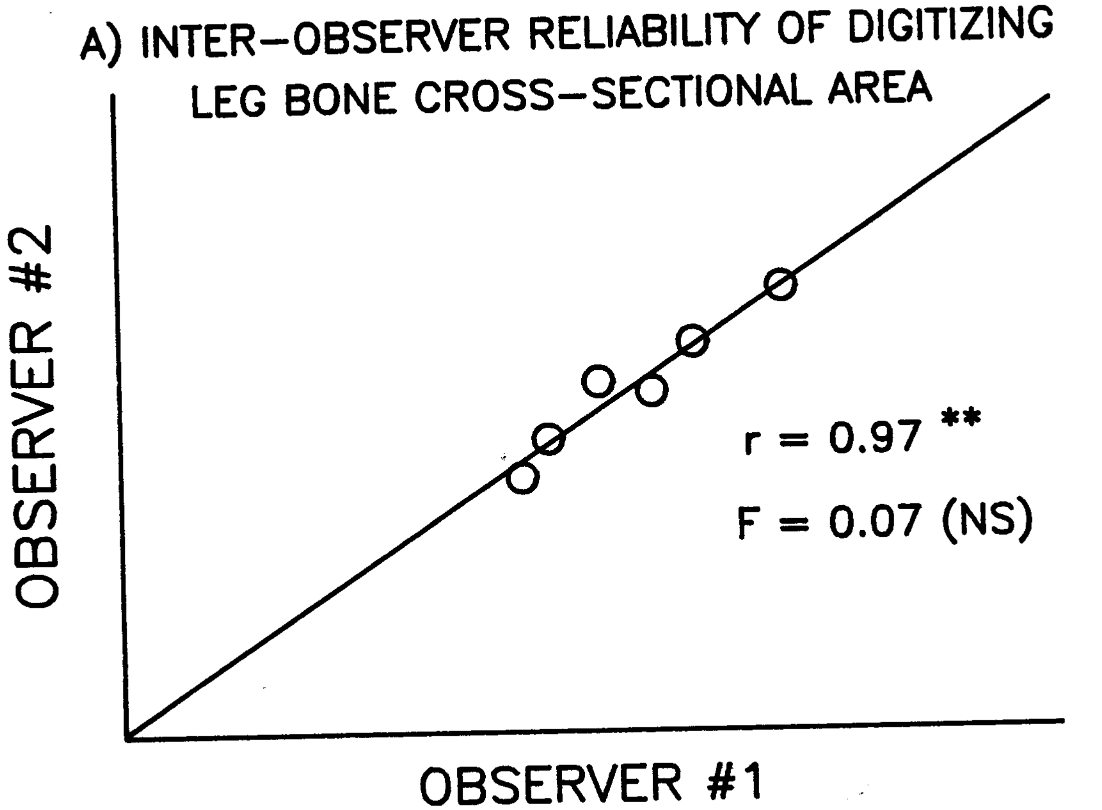
DISCUSSION

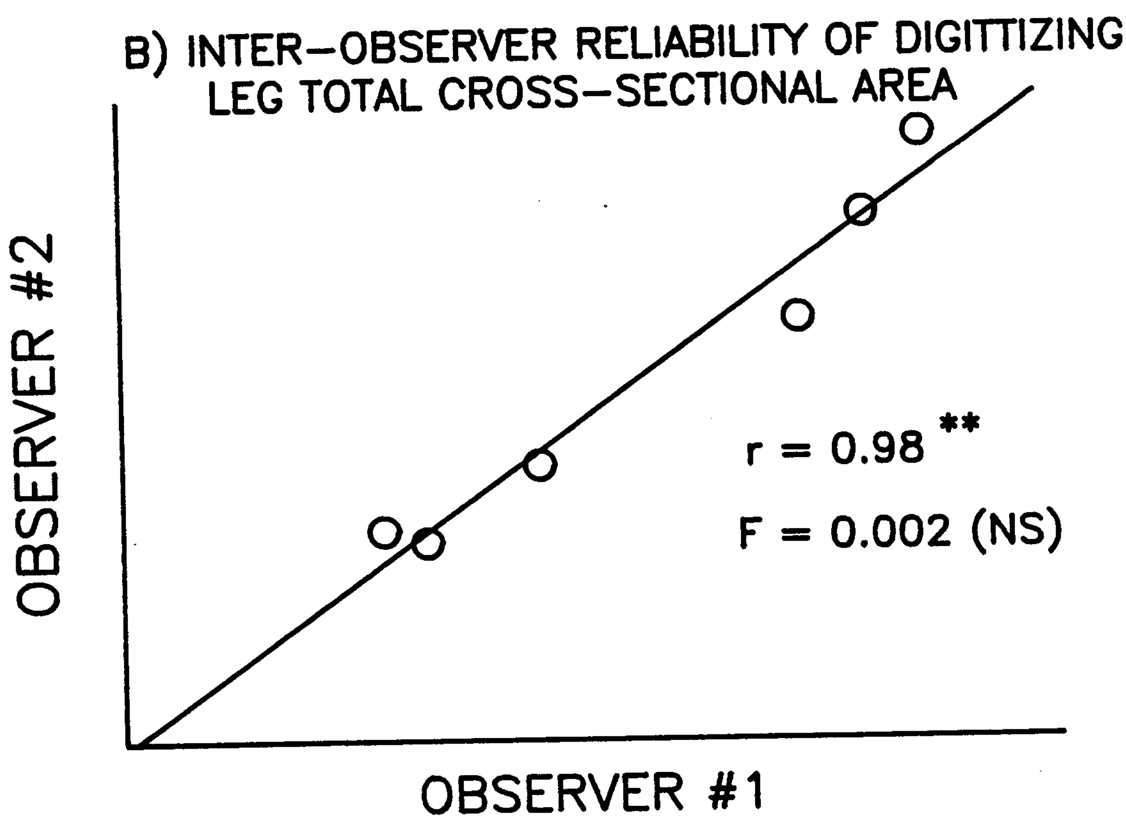
The variability due to a different observer digitizing the areas obtained in this study is very similar to the methodological error (CV = 1.6 %) obtained by Haggmark et al., (1978), in which twenty cross-sectional areas were digitized twice with manual planimetry by the same observer. These results indicate that there is only negligible interobserver variability in the ability to accurately measure CAT areas from the same tracings. In other words, the accuracy of CAT scan measurements are

Table 32. Inter-observer reliability of digitizing technique for bone and total cross-sectional area of the leg. NS = non-significant and S = significant.

SUBJECTS	BONE AREA PERSON#1	BONE AREA PERSON#2	TOTAL AREA PERSON#1	TOTAL AREA PERSON#2
1. D.S.0	11.13	11.00	264.15	270.51
2. J.M.10	9.29	8.93	220.91	224.44
3. J.R.10	10.69	10.25	259.53	261.05
4. M.M.10	10.12	10.40	233.46	232.03
5. D.S.20	12.09	11.84	254.31	248.88
6. J.M.20	9.57	9.52	224.39	223.02
MEAN	10.48	10.32	242.79	243.32
SEM	0.39	0.39	7.02	7.42
SD	0.95	0.94	17.19	18.17
ME	0.17		2.69	
V %	1.61		1.11	
Pearson	r=0.97 (S)		r=0.98 (S)	
ANOVA	F=0.07 (NS) R=0.98 (S)		F=0.002 (NS) R=0.99 (S)	

Figure 18. Inter-observer reliability of digitizing bone and total cross-sectional area of the leg. NS = non-significant.


A) INTER–OBSERVER RELIABILITY OF DIGITIZING
LEG BONE CROSS–SECTIONAL AREA
OBSERVER #2
r = 0.97 **
F = 0.07 (NS)
OBSERVER #1


B) INTER–OBSERVER RELIABILITY OF DIGITTIZING
LEG TOTAL CROSS–SECTIONAL AREA
OBSERVER #2
r = 0.98 **
F = 0.002 (NS)
OBSERVER #1

largely independent of interobserver digitizing errors, given the same initial tracing.

Appendix D : Analysis of variance tables including :

Appendix D-1 : Cross-sectional area (cm^2)
Appendix D-2 : Performance measures
Appendix D-3 : Maximal voluntary isokinetic peak torque
Appendix D-4 : Maximal voluntary isometric peak torque
Appendix D-5 : Peak twitch torque
Appendix D-6 : Isometric peak torque to twitch torque ratio
Appendix D-7 : % motor unit activation
Appendix D-8 : Time related contractile properties

Appendix D-1 - Measure : cross-sectional area (CSA) (CAT)

A.1) Arm bone CSA

Summary of analysis of variance

Source	SS	df	MS	F
Between subjects		24		
Treatment	0.13	1	0.13	0.66
Error	4.52	23	0.20	
Within subjects		25		
Time	0.22	1	0.22	10.6 **
Treat. x Time	6.26-02	1	6.26-02	2.98
Error	0.48	23	2.10-02	

A.2) Elbow flexor lean CSA

Summary of analysis of variance

Source	SS	df	MS	F
Between subjects		24		
Treatment	16.63	1	16.63	1.94
Error	197.12	23	8.57	
Within subjects		25		
Time	4.96	1	4.96	5.95 *
Treat. x Time	6.97-02	1	6.97-02	8.35-02
Error	19.19	23	0.83	

A.3) Lean arm CSA

Summary of analysis of variance

Source	SS	df	MS	F
Between subjects		24		
Treatment	4.20	1	4.20	0.13
Error	743.26	23	32.31	
Within subjects		25		
Time	4.75	1	4.74	4.58
Treat. x Time	0.02	1	0.02	2.35-02
Error	23.82	23	1.03	

A.4) Total arm CSA

Summary of analysis of variance

Source	SS	df	MS	F
Between subjects		24		
Treatment	8.03	1	8.03	2.14-02
Error	8622.27	23	374.88	
Within subjects		25		
Time	8.13	1	8.13	0.23
Treat. x Time	3.21	1	3.13	9.20-02
Error	803.13	23	34.92	

B.1) Leg bone CSA

Summary of analysis of variance

Source	SS	df	MS	F
Between subjects		24		
Treatment	0.41	1	0.41	0.41
Error	23.01	23	1.00	
Within subjects		25		
Time	4.76-04	1	4.76-04	1.19-03
Treat. x Time	1.97-02	1	1.97-02	0.05
Error	9.21	23	0.40	

B.2) Knee extensor lean CSA

Summary of analysis of variance

Source	SS	df	MS	F
Between subjects		24		
Treatment	71.91	1	71.91	0.86
Error	1924.81	23	83.69	
Within subjects		25		
Time	123.20	1	123.20	7.85 *
Treat. x Time	0.24	1	0.24	1.51-02
Error	360.81	23	15.69	

B.3) Lean leg CSA

Summary of analysis of variance

Source	SS	df	MS	F
Between subjects		24		
Treatment	129.65	1	129.65	0.36
Error	8275.81	23	359.82	
Within subjects		25		
Time	238.61	1	238.61	6.87 *
Treat. x Time	1.76	1	1.76	5.05-02
Error	798.38	23	34.71	

B.4) Total leg CSA

Summary of analysis of variance

Source	SS	df	MS	F
Between subjects		24		
Treatment	252.77	1	252.77	0.14
Error	42738.38	23	1858.19	
Within subjects		25		
Time	663.10	1	663.10	10.06 **
Treat. x Time	0.05	1	0.05	7.40-04
Error	1515.50	23	0.05	

Appendix D-2 - Measure : performance measures

A.1) Bench press 1 repetition maximum

Summary of analysis of variance

Source	SS	df	MS	F
Between subjects		22		
Treatment	186.19	1	186.19	2.98
Error	1313.41	21	62.54	
Within subjects		46		
Time	285.52	2	142.76	33.83
Treat. x Time	68.24	2	34.12	8.09 **
Error	177.24	42	4.22	

A.2) Leg press 1 repetition maximum

Summary of analysis of variance

Source	SS	df	MS	F
Between subjects		25		
Treatment	469.02	1	469.02	0.31
Error	35897.56	24	1495.73	
Within subjects		52		
Time	285.52	2	1099.72	23.64
Treat. x Time	68.24	2	454.85	9.78 **
Error	177.24	48	46.52	

A.3) Double arm curl 1 repetition maximum

Summary of analysis of variance

Source	SS	df	MS	F
Between subjects	1043.08	12		
Within subjects	755.29	26		
Time	643.87	2	321.93	69.34 **
Error	111.42	24	4.64	
Total	1798.37	38		

A.4) Double leg extension 1 repetition maximum

Summary of analysis of variance

Source	SS	df	MS	F
Between subjects	6910.20	12		
Within subjects	2450	26		
Time	1155.27	2	577.64	10.71 **
Error	1294.73	24	53.95	
Total	9360.20	38		

B.1) Bench press muscular endurance

Summary of analysis of variance

Source	SS	df	MS	F
Time	660.04	1	660.04	24.35 **
Error	650.46	24	27.10	
Total	1310.5	25		

B.2) Leg press muscular endurance

Summary of analysis of variance

Source	SS	df	MS	F
Time	3301.89	1	3301.89	23.42 **
Error	3384.15	24	141.01	
Total	6686.04	25		

Appendix D-3 - Measure : maximal voluntary isokinetic peak torque

A.1) Elbow flexor peak torque

Summary of analysis of variance

Source	SS	df	MS	F
Between subjects	364.66	1	364.66	3.23
Error	2708.47	24	112.85	
Within subjects				
Velocity	71.75	3	23.92	8.07
Treat. x Vel.	50.81	3	16.94	5.72
Error	213.34	72	2.96	
Time	275.21	2	137.60	10.31
Treat. x Time	114.44	2	57.22	4.29 **
Error	640.36	48	13.34	
Vel. x Time	53.99	6	9.00	4.75
Tre. x Vel. x Tim.	13.06	6	2.18	1.15
Error	273.09	144	1.90	

A.2) Knee extensor peak torque

Summary of analysis of variance

Source	SS	df	MS	F
Between subjects	3365.02	1	3365.02	1.21
Error	64050.13	23	2784.78	
Within subjects				
Velocity	21311.45	3	7103.82	73.75
Treat. x Vel.	68.15	3	22.72	0.24
Error	6645.88	69	96.32	
Time	3534.86	2	1767.43	16.42
Treat. x Time	1929.43	2	964.71	8.96 **
Error	4852.63	46	107.67	
Vel. x Time	118.07	6	19.68	0.48
Tre. x Vel. x Tim.	198.61	6	33.10	0.80
Error	5685.13	138	41.20	

A.3) Elbow flexor relative peak torque

Summary of analysis of variance

Source	SS	df	MS	F
Between subjects	8.89	1	8.89	7.42
Error	27.54	23	1.20	
Within subjects				
Velocity	0.27	3	0.09	2.10
Treat. x Vel.	0.83	3	0.28	6.44
Error	2.95	69	4.28-02	
Time	0.81	1	0.81	1.96
Treat. x Time	2.34	1	2.34	5.68 **
Error	9.47	23	0.41	
Vel. x Time	0.36	3	0.12	3.35
Tre. x Vel. x Tim.	2.57-02	3	8.57-03	0.24
Error	2.45	69	3.54-02	

A.4) Knee extensor relative peak torque
isokinetic torque

Summary of analysis of variance

Source	SS	df	MS	F
Between subjects	0.21	1	0.21	3.23
Error		22	0.79	
Within subjects				
Velocity	9.00	3	3.00	8.07
Treat. x Vel.	2.99-03	3	9.97-03	5.72
Error	2.65	66	4.01-02	
Time	0.45	1	0.45	10.31
Treat. x Time	1.33	1	1.33	4.29 **
Error	3.07	22	0.14	
Vel. x Time	0.03	3	8.94-03	4.75
Tre. x Vel. x Tim.	5.37-02	3	1.79-02	1.15
Error	1.87	66	2.83-02	

Appendix D-4 - Measure : maximal voluntary isometric peak torque

A.1) Elbow flexor peak torque

Summary of analysis of variance

Source	SS	df	MS	F
Between subjects	229.44	1	229.44	1.42
Error	3890.59	24	162.11	
Within subjects				
Angles	3369.05	3	1123.02	225.08
Treat. x Ang.	6.47	3	2.16	0.43
Error	359.23	72	4.99	
Time	573.59	2	286.80	45.88
Treat. x Time	176.34	2	88.17	14.11 **
Error	300.04	48	6.25	
Ang. x Time	14.36	6	2.39	1.37
Tre. x Ang. x Tim.	23.70	6	3.94	2.26 *
Error	252.16	144	1.75	

A.2) Knee extensor peak torque

Summary of analysis of variance

Source	SS	df	MS	F
Between subjects	153.36	1	153.36	5.20-02
Error	70788.13	24	2949.51	
Within subjects				
Angles	181779.70	3	60593.23	181.50
Treat. x Ang.	116.90	3	38.97	0.12
Error	24037.25	72	333.85	
Time	1418.016	2	709.01	6.47
Treat. x Time	476.43	2	238.21	2.17
Error	5263.38	48	109.65	
Ang. x Time	1448.89	6	241.48	5.44
Tre. x Ang. x Tim.	781.73	6	130.29	2.94 *
Error	6385.13	144	44.34	

A.3) Elbow flexor relative peak torque

Summary of analysis of variance

Source	SS	df	MS	F
Between subjects	6.41	1	6.41	4.41
Error	33.43	23	1.45	
Within subjects				
Angles	33.82	3	11.27	170.43
Treat. x Ang.	0.25	3	8.48-02	1.28
Error	4.56	72	6.61-02	
Time	3.53	2	3.53	13.06
Treat. x Time	1.83	2	2.83	10.45 **
Error	6.22	48	0.27	
Ang. x Time	5.85-02	6	1.95-02	0.63
Tre. x Ang. x Tim.	0.41	6	0.14	4.42 **
Error	2.13	144	3.09-02	

A.4) Knee extensor relative peak torque

Summary of analysis of variance

Source	SS	df	MS	F
Between subjects	0.74	1	0.74	1.19
Error	14.35	23	0.62	
Within subjects				
Angles	76.01	3	25.34	193.05
Treat. x Ang.	0.38	3	0.13	0.98
Error	9.06	69	0.13	
Time	2.74-02	1	2.74-02	0.37
Treat. x Time	0.21	1	0.21	2.90
Error	1.69	23	0.7	
Ang. x Time	0.24	3	7.92-02	2.49
Tre. x Ang. x Tim.	0.52	3	0.17	5.44 **
Error	2.19	69	3.17-02	

Appendix D-5 - Measure : peak twitch torque

A.1) Elbow flexor peak torque

Summary of analysis of variance

Source	SS	df	MS	F
Between subjects	11.90	1	11.90	2.95
Error	70788.13	24	4.03	
Within subjects				
Angles	4.10	3	1.37	19.22
Treat. x Ang.	1.90-02	3	6.35-03	8.94-02
Error	5.11	72	0.07	
Time	8.43	2	4.22	19.03
Treat. x Time	3.73	2	1.86	8.41 **
Error	10.64	48	0.22	
Ang. x Time	0.46	6	7.63-02	2.75
Tre. x Ang. x Tim.	0.20	6	3.28-02	1.18
Error	4.00	144	2.78-02	

A.2) Knee extensor peak torque

Summary of analysis of variance

Source	SS	df	MS	F
Between subjects		24		
Treatment	198.16	1	198.16	1.28
Error	3553.92	23	154.52	
Within subjects		50		
Time	145.68	2	72.84	8.88
Treat. x Time	58.03	2	29.02	3.53 *
Error	377.53	46	6.35-03	

A.3) Elbow flexor relative peak torque

Summary of analysis of variance

Source	SS	df	MS	F
Between subjects	0.33	1	364.66	8.47
Error	0.90	23	112.85	
Within subjects				
Velocity	4.92-02	3	1.64-02	20.11
Treat. x Vel.	3.21-03	3	1.07-03	1.31
Error	5.64-02	69	8.16-04	
Time	2.02-02	1	2.02-02	6.33
Treat. x Time	4.51-02	1	4.52-02	14.18
Error	7.32-02	23	3.19-03	
Vel. x Time	3.57-03	3	1.19-03	14.18 **
Tre. x Vel. x Tim.	3.76-04	3	1.25-04	1.15
Error	2.35-02	69	3.41-04	

A.4) Knee extensor relative peak torque

Summary of analysis of variance

Source	SS	df	MS	F
Between subjects		23		
Treatment	3.10-02	1	3.10-02	1.28
Error	0.65	22	2.97-02	
Within subjects		24		
Time	2.50-02	1	2.50-02	8.88
Treat. x Time	9.52-03	1	9.52-03	3.53 *
Error	0.12	22	5.48-03	

Appendix D-6 - Measure : Isometric MVC peak torque to twitch torque ratio

A.1) Elbow flexor ratio

Summary of analysis of variance

Source	SS	df	MS	F
Between subjects	58.40	1	58.40	1.81
Error	776.23	24	32.34	
Within subjects				
Angles	1297.12	3	432.37	88.29
Treat. x Ang.	26.07	3	8.69	1.77
Error	352.58	72	4.90	
Time	116.31	2	58.16	6.36
Treat. x Time	58.87	2	29.43	3.22 *
Error	439.00	48	9.15	
Ang. x Time	30.57	6	5.09	2.48
Tre. x Ang. x Tim.	5.57	6	.93	0.45
Error	295.80	144	2.05	

A.2) Leg ratio

Summary of analysis of variance

Source	SS	df	MS	F
Between subjects		24		
Treatment	20.01	1	20.01	4.58
Error	100.42	23	4.37	
Within subjects		50		
Time	2.15	2	1.08	0.61
Treat. x Time	2.66	2	1.33	0.75
Error	81.45	46	1.77	

Appendix D-7 - Measure : % motor unit activation

A.1) Elbow flexor % motor unit activation (experimental group)

Fiedman two-way anova by ranks

PRE-TRAINING SUM RANKS =	21.5	MEAN RANK =	1.65
MID-TRAINING SUM RANKS =	29	MEAN RANK =	2.23
POST-TRAINING SUM RANKS =	27.5	MEAN RANK =	2.11

N = 13 K = 3
CHI-SQUARE = 2.42 (df = 2)

Probability of chance occurrence of this Chi-square = 0.298

A.2) Elbow flexor % motor unit activation (control group)

Fiedman two-way anova by ranks

PRE-TRAINING SUM RANKS =	25.5	MEAN RANK =	1.96
MID-TRAINING SUM RANKS =	27	MEAN RANK =	2.08
POST-TRAINING SUM RANKS =	25.5	MEAN RANK =	1.96

N = 13 K = 3
CHI-SQUARE = 0.12 (df = 2)

Probability of chance occurrence of this Chi-square = 0.944

B.1) Knee extensor % motor unit activation (experimental group)

Fiedman two-way anova by ranks

PRE-TRAINING SUM RANKS =	18	MEAN RANK =	1.5
MID-TRAINING SUM RANKS =	27.5	MEAN RANK =	2.29
POST-TRAINING SUM RANKS =	26.5	MEAN RANK =	2.21

N = 12 K = 3
CHI-SQUARE = 4.54 (df = 2)

Probability of chance occurrence of this Chi-square = 0.103

B.2) Knee extensor % motor unit activation (control group)

Fiedman two-way anova by ranks

PRE-TRAINING SUM RANKS =	24	MEAN RANK =	1.85
MID-TRAINING SUM RANKS =	27.5	MEAN RANK =	2.12
POST-TRAINING SUM RANKS =	26.5	MEAN RANK =	2.04

N = 12 K = 3
CHI-SQUARE = 0.5 (df = 2)

Probability of chance occurrence of this Chi-square = 0.779

Appendix D-8 - Measure : time-related contractile properties

A.1) Elbow flexor time to peak torque

Summary of analysis of variance

Source	SS	df	MS	F
Between subjects	2957.96	1	2957.96	5.22
Error	13032.5	23	566.63	
Within subjects				
Angles	2192.58	3	730.86	9.48
Treat. x Ang.	458.35	3	152.86	1.98
Error	5317.13	69	77.06	
Time	117.59	2	58.79	0.39
Treat. x Time	617.57	2	308.78	2.09
Error	6781.13	46	147.42	
Ang. x Time	494.13	6	82.35	1.14
Tre. x Ang. x Tim.	269.88	6	44.98	0.62
Error	9943.25	138	72.05	

A.2) Elbow flexor half-relaxation time

Summary of analysis of variance

Source	SS	df	MS	F
Between subjects	1059.63	1	1059.63	1.06
Error	22889.38	23	995.1903	
Within subjects				
Angles	17602.84	3	5867.62	32.73
Treat. x Ang.	262.28	3	87.43	0.49
Error	12370.38	69	179.28	
Time	212.94	2	106.47	0.45
Treat. x Time	21.84	2	10.92	4.64-02
Error	10809.38	46	234.99	
Ang. x Time	392.34	6	65.39	0.70
Tre. x Ang. x Tim.	512.655	6	85.44	0.91
Error	12936.38	138	93.74	

A.3) Elbow flexor total contraction time

Summary of analysis of variance

Source	SS	df	MS	F
Between subjects	7475.13	1	7475.13	4.49
Error	38317.00	23	1665.96	
Within subjects				
Angles	8241.09	3	2747.03	15.79
Treat. x Ang.	167.7	3	55.9	0.32
Error	12005.00	69	173.99	
Time	780.00	2	390.00	1.36
Treat. x Time	705.90	2	352.95	1.23
Error	13235.00	46	287.71	
Ang. x Time	461.37	6	76.90	0.94
Tre. x Ang. x Tim.	322.92	6	53.82	0.65
Error	11344.00	138	82.21	

A.4) Elbow flexor maximum rate of torque development

Summary of analysis of variance

Source	SS	df	MS	F
Between subjects	21372.1	1	21372.1	5.79
Error	84915.75	23	3691.99	
Within subjects				
Angles	7671.59	3	2557.2	14.21
Treat. x Ang.	257.50	3	85.83	0.48
Error	12417.00	69	179.96	
Time	6881.75	2	3440.88	10.05 **
Treat. x Time	1905.35	2	952.67	2.78
Error	15746.38	46	342.31	
Ang. x Time	353.44	6	58.91	0.83
Tre. x Ang. x Tim.	237.12	6	38.52	0.56
Error	9733.88	138	70.53	

A.5) Elbow flexor maximum rate of torque relaxation

Summary of analysis of variance

Source	SS	df	MS	F
Between subjects	1692.91	1	1692.91	4.73
Error	8231.8	23	357.90	
Within subjects				
Angles	617.77	3	205.92	9.76
Treat. x Ang.	23.24	3	7.75	0.37
Error	1455..02	69	21.09	
Time	337.48	2	168.74	4.88 *
Treat. x Time	314.03	2	157.02	4.54 *
Error	1590.45	46	34.58	
Ang. x Time	134.42	6	22.40	1.17
Tre. x Ang. x Tim.	125.62	6	20.94	1.10
Error	2631.73	138	19.07	

B.1 Knee extensor time to peak torque

Summary of analysis of variance

Source	SS	df	MS	F
Between subjects		24		
Treatment	233.2	1	233.2	0.85
Error	6329.19	23	275.18	
Within subjects		50		
Time	2115.38	2	1057.69	6.54 **
Treat. x Time	2558.53	2	279.26	1.73
Error	7442.25	46	161.79	

B.2 Knee extensor half-relaxation time

Summary of analysis of variance

Source	SS	df	MS	F
Between subjects		24		
Treatment	1219.29	1	1219.29	0.97
Error	28951.84	23	1258.78	
Within subjects		50		
Time	2245.23	2	1122.62	2.31
Treat. x Time	1556.49	2	778.25	1.60
Error	22343.34	46	485.73	

B.3) Knee extensor total contraction time

Summary of analysis of variance

Source	SS	df	MS	F
Between subjects		24		
Treatment	595.92	1	595.92	0.36
Error	38360.38	23	1667.84	
Within subjects		50		
Time	30.42	2	15.21	2.59-02
Treat. x Time	525.92	2	262.96	0.45
Error	27006.13	46	587.09	

B.4) Knee extensor maximum rate of torque development

Summary of analysis of variance

Source	SS	df	MS	F
Between subjects		24		
Treatment	272884.5	1	272884.5	2.03
Error	3102814	23	134905	
Within subjects		50		
Time	360205.5	2	180102.80	9.02 **
Treat. x Time	54283.32	2	27141.66	1.36
Error	918256	46	19962.09	

B.5) Knee extensor maximum rate of torque relaxation

Summary of analysis of variance

Source	SS	df	MS	F
Between subjects		24		
Treatment	36283.65	1	36283.65	1.12
Error	746387	23	32451.61	
Within subjects		50		
Time	45699.03	2	22849.51	3.01
Treat. x Time	4392.57	2	2196.29	0.29
Error	349735	46	7602.94	