NORMALISED MUSCLE FORCE AND RELAXATION RATES IN SUBNOURISHED AND AGED HUMAN SUBJECTS

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ABSTRACT: NORMALISED MUSCLE FORCE AND RELAXATION RATES IN SUBNOURISHED AND AGED HUMAN SUBJECTS

Is the muscle weakness associated with ageing and subnutrition simply due to muscle atrophy? Can the weakness be reversed by training?

Maximal voluntary force (MVF) measurements of adductor pollicis (AP) muscle were made during maximum voluntary contractions (MVC's) and normalised for anatomical cross-sectional area (CSA) in three subject groups: normally-nourished young; normally-nourished elderly; and subnourished young patients. In the subnourished patients MVF was significantly less, relative to their heights, than in the young control group but normalised force (MVF/CSA) was unchanged. Normal maximum relaxation rates (MRR) were significantly slower in the patients than in the controls.

The elderly also showed significantly reduced MVF relative to their heights and in addition the mean ratio of MVF/CSA for the elderly was significantly less than that for the young nourished. MRR was no different in the two groups.

A comparison was made of AP muscle CSA's measured directly (by means of CAT and n.m.r scans) with muscle CSA's measured by the method used in the present, reported studies. There was a good correlation between CSA's obtained by CAT/n.m.r. and the method used in the present studies, indicating that the present method gives a good estimate of AP muscle CSA.

An evaluation was made of the effectiveness of an adductor pollicis strength training regime for future use in investigating the effects of strength training on aged muscle. No training effect was found. The experience gained prompted the development of an improved force measuring apparatus.

An investigation was made into the force and cross-sectional area characteristics of the AP in a group of experienced fencers. This was intended as a means of evaluating the use of the newly-developed force-measuring apparatus, and as a preliminary to an intended training study of AP in the elderly. The new force-measuring apparatus gave a better correlation with measured AP muscle CSA's than did the old-style force transducer. No training effect was found in the AP of the fencers' fencing hand.

Using the new, improved force measuring apparatus, a group of normally-nourished elderly and a group of normally-nourished young were tested for maximality of their muscle recruitment by means of twitch superimposition. There was a strong indication that both groups were able to maximally activate their adductor pollicis muscle during maximum voluntary contraction.

It appears that in the young subnourished at least, the weakness associated with subnourishment is due largely to atrophy.

2(b)

It is evident that the muscle weakness associated with age is not due simply to muscle atrophy. There is in the elderly an inherent decline in the force-producing capability of AP muscle.

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I would also like to thank Dr. Stuart Bruce and Dr. Suzanne Phillips, both of whom co-worked with the author in the large part of this reported work. (The sections concerning strength training and grip strength in trained fencers report on work done by the author alone [with the supervision and advice of Professor Woledge].)

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1. INTRODUCTION

Muscle weakness is associated with ageing (Larsson, 1978) and subnutrition (Daniel et al., 1977). Is age-related weakness due in part to subnutrition? Can the effects on muscle of subnutrition and ageing be separated and quantified? Can the effects of ageing be reversed by training?

1.1 Factors Affecting Changes in Muscle Force

The following factors could be the principal causes of muscle force changes with ageing:

i. Atrophy -- a decline in the absolute amount of contractile material in the muscle, with or without the replacement of the contractile material by non-contractile tissue.

ii. Changes in ability to activate -- a change in the degree to which a muscle can be voluntarily activated, resulting in a corresponding change in the amount of force which can be voluntarily exerted by that muscle.

iii. Loss of specific force in fully activated muscle -- a decline in the ability of a muscle to exert force as measured per unit cross sectional area of that muscle.

These possible mechanisms will be discussed in the following pages.

1.2 Decline in force production with ageing

It is well established that there is an age-related decline in the force-producing ability of human muscle (Larsson, 1978), though the mechanism of the decline is poorly understood. Decline in maximum voluntary force with ageing could be due to;

i. Atrophy, possibly caused by;

I. A decline over time in the customary use of muscles (Rode and Shephard, 1971; Petrovsky and Lind, 1979).

II. A change in the sensitivity of the mechanism linking maintenance of muscle mass to its usage, so that although usage may continue close to or at its customary level, the muscle atrophies.

ii. Inability to voluntarily activate.

It is possible that inability to fully voluntarily activate a muscle may be more common in the elderly than in the young. There is some evidence for an increase in perceived exertion with ageing (Borg and Linderholm, 1967). This factor may be of importance in voluntary testing of strength in the elderly; it raises the question as to whether or not the elderly, voluntarily contracting muscle is fully activated.

Studies of strength training in the elderly have been few, but seem to indicate that the amount of strength increase during training in the elderly may be less than in younger subjects (Moritani and de Vries, 1978; 1980). This may be due to a greater frequency of incomplete activation of muscle in the elderly than in the young.

iii. Loss of specific force.

Specific force may decrease over time due to:

I. Fibre-type changes -- there may be a selective, time-dependent loss and/or decrease in size of type 2 muscle fibres (Larsson et al., 1979; Lexell et al., 1988). Type 2 fibres may, with ageing, transform to type 1 fibres. This process may be linked to atrophy and/or loss of motor neurones with ageing (Campbell et al., 1973). However, disagreement exists as to whether type 2 fibres are intrinsically stronger than type 1 fibres (Jones et al., 1989; Clarkson et al., 1981; Aniannsson et al., 1981; Larsson, 1978).

II. Muscle geometry changes -- changes over time in the angle at which muscle fibres attach to their tendons may alter the force measured between the ends of the muscle. Resolving the force along the tendon, the resultant is proportional to the cosine of the angle of pennation (Theta). A change of 5-10 degrees would not make much difference to the force measured between the ends of the muscle. However, as the angle of pennation decreases, less contractile material can be attached in parallel between the two tendons. Therefore, for an angle of pennation theta, the force transmitted in the tendon as a result of muscle contracting will be proportional to sine 2 theta (Alexander and Vernon, 1975). Therefore, a change in theta from 20-15 degrees would decrease the force generated by the muscle by 28%.

Therefore, if, over time, fibres atrophy and thus attach to the tendon at a lesser angle, then the decrease in strength could be greater than the overall decrease in muscle cross sectional area.

III. Replacement of contractile material with intracellular or extracellular non-contractile material, such as collagen or lipoproteins.

IV. Changes in the inherent force-producing ability of the individual myofibrils (Brooks & Faulkner, 1988; Phillips et al, 1991).

1.3 Changes in Muscle Function in the Subnourished

Age-related muscle changes may be additionally influenced by changes in nutritional status.

It is accepted that muscle wasting is linked to undernutrition (Daniel et al., 1977). Also, recent studies have suggested that various changes of muscle function, such as relaxation rate, maximum isometric force, force:frequency relationship and fatiguability, may be implicated with subnutrition or changes in nutritional status (Chan et al., 1986; Lopes et al., 1982; Russell et al., 1983a, 1983b).

There have been some apparent contradictions in study findings. Newham, et al. (1986), found no changes in maximum isometric force, force:frequency relationship, maximum relaxation rate, or fatiguability in a group of obese subjects on a hypocaloric diet. However, no studies to date have taken muscle size into account. Although it might be expected that muscle size alone would not be related to fatigue or force:frequency relationships, an understanding of the relationship of size to force is essential in comparisons between individuals of muscle force measurements.

1.4 Strength training in the elderly.

It has been claimed that the amount of strength increase in the elderly (65+) may be less than in younger subjects (Moritani and de Vries, 1978; 1980). This may be due to a greater frequency of incomplete activation of the muscle in the elderly (c.f. 1.2 (ii) above) than in the young. (However, Brown et al. (1990) demonstrated that elderly men between the ages of 60 and 70 retained the same potential for strength increase and hypertrophy of their elbow flexors in response to dynamic training as young men).

Heavy resistance training makes muscles stronger (Costill et al, 1979; Delorme, 1945; Thorstensson et al, 1976; Duchateau and Hainault, 1984). However, there is poor correlation between increases in muscle bulk consequent upon resistance training, either isometric or dynamic, and strength changes (MacDougall et al, 1980). Strength increases disproportionately to muscle bulk increase (Davies et al, 1988; Ikai and Fukunaga, 1970; Jones et al., 1989; Goldberg et al, 1975). This poor correlation could be for the following reasons:

Changes in ability to activate -- an increase in activation of the muscle (assuming the muscle is not being fully activated prior to training). Studies measuring surface EMG during maximal contractions (from whence have come evidence for such changes) differ in results. Moritani and de Vries (1978) and Hakkinen and Komi (1985) report increase in maximal EMG with training. Komi and Buskirk (1972) and Thorstensson et al (1976) report no change (or decrease) in maximal EMG with training.

Learning effect -- it is possible that more complex movements carried out as training involve a significant training component (Rutherford and Jones, 1986). Training may bring about better use of muscles accessory to the muscle or muscles being trained. Ikai and Fukunaga (1970) in their training study using the elbow flexors (voluntary isometric contractions) found a cross-over in force increase to the untrained control arm, which suggests that at least part of the strength increase found was due to learning effects. Davies et al. (1988) studying the elbow flexors (voluntary, isometric) and Rutherford and Jones (1986) studying quadriceps (voluntary, isometric) found no cross-over. Both Rutherford and Davies tested their subjects before and during training to ensure full muscle activation, by means of twitch interpolation, as described by Merton (1954). Ikai et al.(1976) did not ensure full voluntary activation of elbow flexors of their subjects before training.

Increase in specific force -- preferential hypertrophy of type 2 fibres. (c.f 1.2 (iii) I.)

Packing of contractile material within the muscle fibre could increase with training. Penman (1970) reported an increased number of actin filaments surrounding myosin. Results were not, however, considered conclusive, due to the limited nature of the data.

Davies et al. (1988) found small (non-significant) differences in muscle density following training. The role of muscle density change as explanation of the lack of correlation of strength increases with hypertrophy in resistance training remains inconclusive.

Changes in the angle at which muscle fibres attach to their tendons may alter the force measured between the ends of the muscle. (c.f. 1.2 (iii) II).

It is known that work-induced hypertrophy increases collagen synthesis in animal muscle (Schiaffino et al., 1972; Goldberg et al., 1975). This increased connective tissue content may play a part in transmission of force in the muscle: tension is transmitted longitudinally in a muscle fibre through serial sarcomeres, and the force is proportional to the muscle cross-sectional area and independent of its length. If, however (upon training) connective tissue attachments were made between the tendons and intermediate sarcomeres,

this would bring about an increase in the force generated per unit cross-sectional area of the muscle (Fig. 1).

1.5. Aims of this study

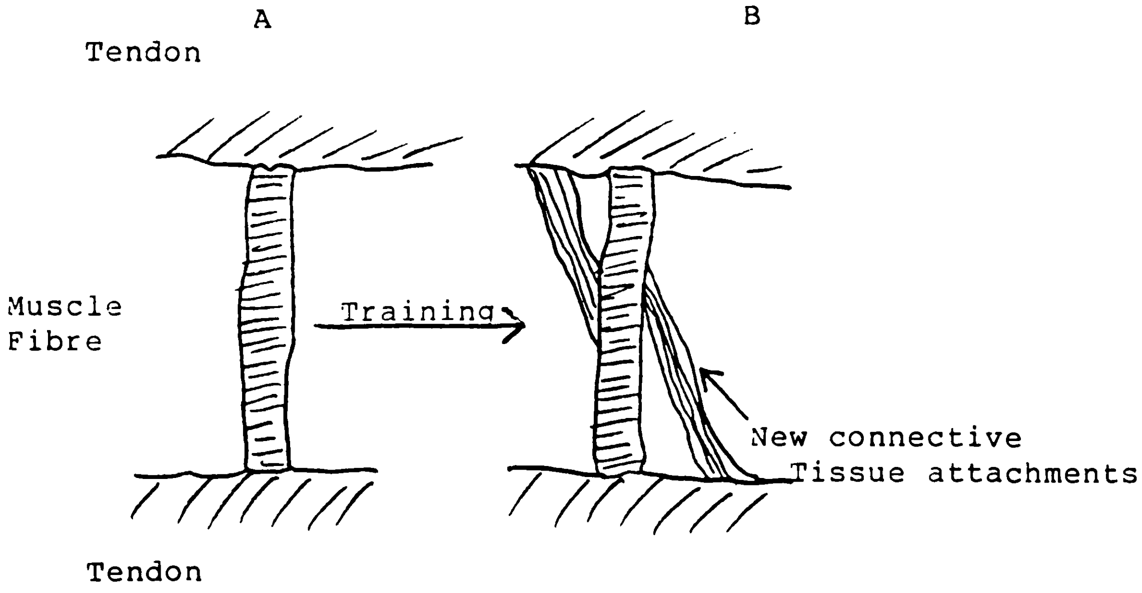
The primary aim of this study is to attempt to quantify and separate the effects of subnutrition and ageing on the human adductor pollicis and first dorsal interosseous muscle, and secondarily to evaluate the effectiveness of an adductor pollicis strength training regime for future use in investigating the effects of strength training on aged muscle.

This muscle group is particularly suitable for this purpose for the following reasons:

i. Fibre composition of adductor pollicis is more nearly homogenous (80% - 100% type 1) than, for instance, the quadriceps (approximately equal proportions of both fibre types) (Round et al, 1984); any preferential hypertrophy of type 2 fibres upon training or time-dependent loss or transformation with ageing would be minimised. The possible effects of fibre transformation as a factor in specific force loss with ageing and selective type 2 fibre hypertrophy as a factor in specific force gain in strength training would thus be largely eliminated.

ii. Methods of measuring the strength (maximal isometric) and cross-sectional area of adductor pollicis

Fig 1. Connective tissue attachments: A possible mechanism of force transmisssion



Before training (A): The muscle fibre has no connection with connective tissue attachments. Upon contraction, force is directly transmitted through the fibre to the tendonous attachments.

After training (B): Connective tissue attachments are made between the tendons and intermediate sarcomeres. The fibre is now effectively doubled in cross-sectional area, acting in effect as two fibres in parallel. (in consequence, the effective length of the fibre is halved).

have been developed (Bruce et al., 1986a), which give good correlation between strength and muscle size in a group of healthy young volunteers. Comparison of muscle force with bulk of the same muscle or group of muscles is necessary in order to determine the relative contributions of atrophy and specific change to measurements of MVC in ageing muscle and hypertrophy and specific change in trained muscle. The ratio of MVC to CSA should not change with atrophy or hypertrophy.

The nature of the force-measuring apparatus is such that the point of application of force is close to the insertion of adductor pollicis, so that the effect of differing lever arms either between subjects or as a result of age-dependent changes or upon training will be minimised.

iii. Despite an arguable decrease in general level of activity with age, it might be expected that decline in the usage of muscles in the hand may be less than decline of usage of the leg muscles or the proximal muscles of the arms. It would be advantageous to study a muscle in which disuse atrophy is minimised; a large amount of atrophy may make specific force changes difficult to detect.

iv. Adductor pollicis is a near-parallel fibred muscle. Measurements of MVC and muscle bulk in muscles and muscle groups other than adductor pollicis have been subject to error because of lever systems, including fiber pennation; measurements of MVF and CSA in humans have often resulted in low correlation coefficients (Maughan et al., 1983; Young et al., 1984, 1985). Adductor pollicis, almost parallel fibred (and easily accessible for CSA measurements) gives a strong correlation coefficient ($r=0.926$, $P<0.001$) (Bruce et al., 1986b).

To address the aims of this study, a comparison was made of maximum voluntary force, muscle cross-sectional area and maximum relaxation rate in young healthy; young subnourished; and elderly healthy volunteers.

Results from the above prompted an investigation into the degree of muscle activation in the young and elderly during testing for maximum voluntary contractions.

A pilot training study was carried out into the response of young healthy volunteers to isometric training of adductor pollicis.

An investigation was also made of AP CSA and MVF in the fencing and non-fencing hands of experienced fencers. This was done as a means of evaluating the performance of newly-developed force-measuring apparatus, and as a preliminary to an intended training study of AP in the elderly.

A comparison study was made between CSAs measured by potentiometry and by CAT/n.m.r.

Throughout the reported studies, unless otherwise stated, significance was assessed by Student's t-test and the results labelled significant where $P<0.05$. Regression was calculated from standard methods.

The data in the reported work appear to be normally distributed. MVF and CSA were examined in both male and female subjects seperately, in the largest group available for analysis. The distribution of MVF and CSA appeared to be symettrical in both groups.

In the reported work, where 'adductor pollicis' or 'AP' is mentioned, it may be taken to mean 'adductor pollicis and first dorsal interroseous'. This abbreviation is used for simplicity alone.

METHODS

PART A: Effect of subnutrition on normalised muscle force and relaxation rate

2.1 Subjects

Twenty seven normally nourished healthy subjects (age range 18 - 39 years, mean 26 years, 10 male, 17 female) were recruited, staff and students at University College London. Volunteers were selected so as to give as wide a range of height and frame size as possible.

Nine subnourished patients, known to be chronically less than 90% of ideal body weight for height and frame size were tested (age range 19 - 54 years, mean 30 years, 5 males, 4 females). They were recruited from patients and outpatients at St. Helens Hospital, Hastings, University College Hospital, London, and Guy's Hospital, London. Seven had Crohn's disease, one had ulcerative colitis, and one had short bowel syndrome. Their percentage ideal body weights at the time of testing ranged from 76.4 to 89% (mean 85.5%).

Percentage Ideal Body Weight was calculated using the equation:

$$\% \text{ IBW} = \frac{\text{Actual Body Weight}}{\text{IBW}} \times 100$$

IBW was determined using standard tables (Grant, 1980).

Two of the subjects were on steroids at the time of testing. Patients with specific muscle diseases, osteomalacia or thyroid disease were excluded.

All subjects gave informed consent verbally. The project was approved by the ethical committees at University College London, Hastings Health Authority and Guy's Hospital.

2.2 Clinical examination

The subjects were clinically screened (by geriatrician S.A. Bruce). Those with specific muscle diseases, osteomalacia, pain or stiffness of movement of the thumb, or thyroid disease, were excluded. Subjects' percentage ideal body weight were determined using measurements of the subject's height and wrist circumference and ideal body weight tables.

The force and area measurement procedures were explained to the subject.

2.3 Force measurement

MVC's were measured using a strain gauge bridge circuit (Fig. 2). The gauge is mounted in the centre of a small brass plate which is seated in a brass cylinder. A rod which opposes thumb adduction at the base of the proximal phalanx, runs down inside the cylinder and depresses the plate when force is applied. The system is insensitive to sideways forces applied to the cylinder. The other end of the cylinder is applied to a ball-bearing mounted in a perspex hand splint so as to lie between the index and middle fingers. The splint prevents flexion of the fingers about the metacarpophalangeal joints, minimising as far as possible any contribution to the recorded force from the finger flexor muscles. The point of opposition of adduction of

Fig. 2. Force measuring apparatus (strain gauge bridge circuit.

Strain gauge (inside brass cylinder)

Saddle, positioned at base of proximal phalange.

Ball-bearing mount.

Perspex hand splint.

Foam padding.

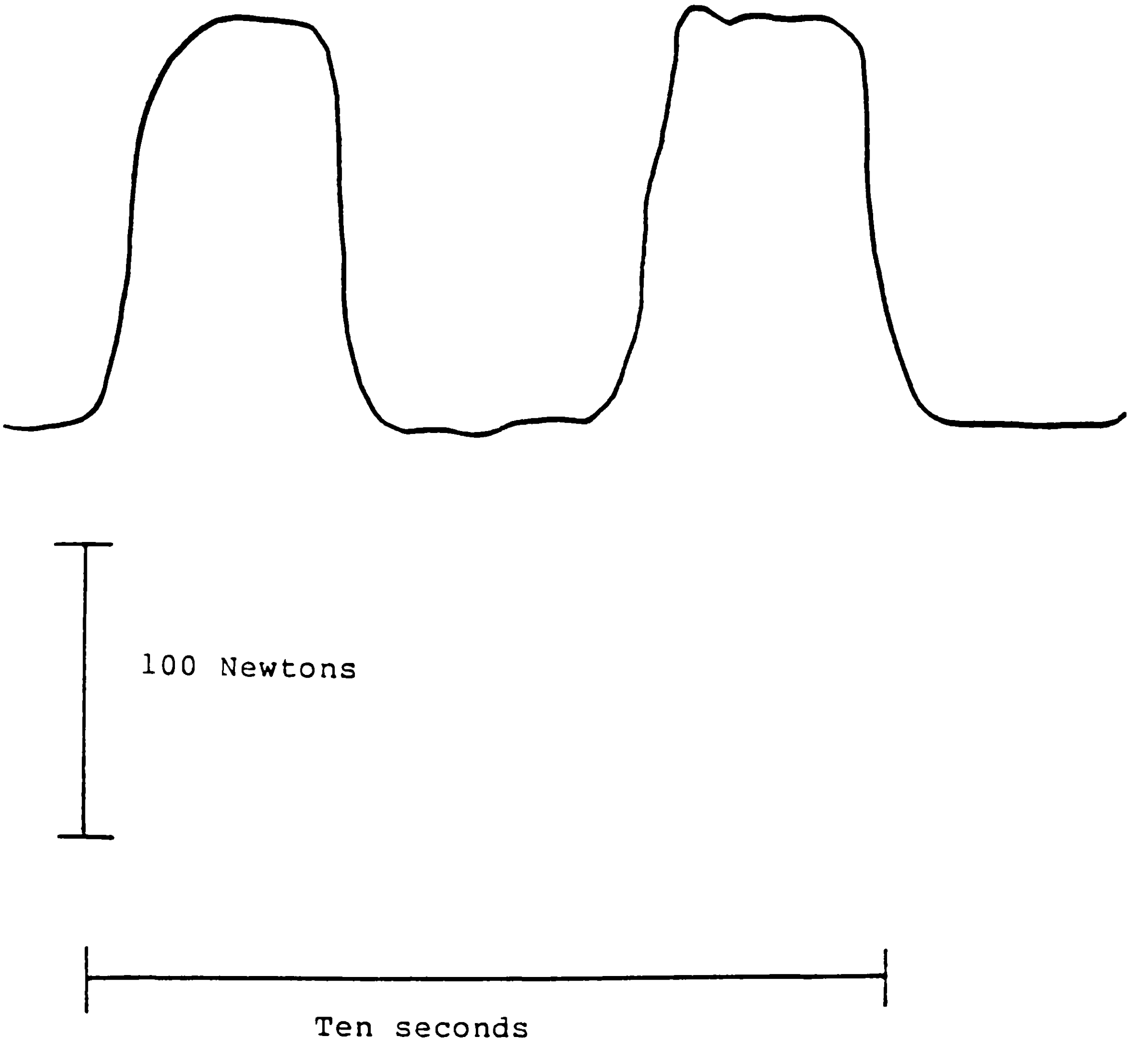
the thumb was chosen because it is close to the attachment of adductor pollicis and proximal to the attachments of the flexor muscles of the thumb. Therefore, the force measured is largely due to the activity of adductor pollicis, with probable contribution from the first dorsal interosseous. The subject's hand was immersed in warm water for 5 minutes. This was done to exclude the possibility of muscle temperature differences between subjects influencing the muscle's force-producing ability (Raratunga, et al., 1987).

The hand was clamped into the force-measuring frame, firmly but not painfully. The metacarpo-phalangeal joint was positioned directly under the perspex bar. The 'saddle' was positioned as near as possible to the base of the proximal phalanx of the first metacarpal. The thumb was positioned in near-to-full abduction, as indicated by the point in the process of adduction from full abduction where the web between the 1st and 2nd metacarpal starts to crumple.

The subject had a trial squeeze, to accustom him/herself to the apparatus. The subject gave nine contractions, consisting of three contractions/trace, each contraction being of 1.5 to 2 seconds duration, seperated by a two second rest. (No signs of fatigue were apparent during such groups of contractions). Subjects were encouraged to relax without delay at the end of each contraction. Verbal encouragement was given to the subject before and during contraction, and the subject was allowed to see the traces on the oscilloscope screen. A sample sweep is shown in Fig. 3.

Data was collected either on a Nicolet 3091 portable

Fig. 3. Sample MVF oscilloscope trace.



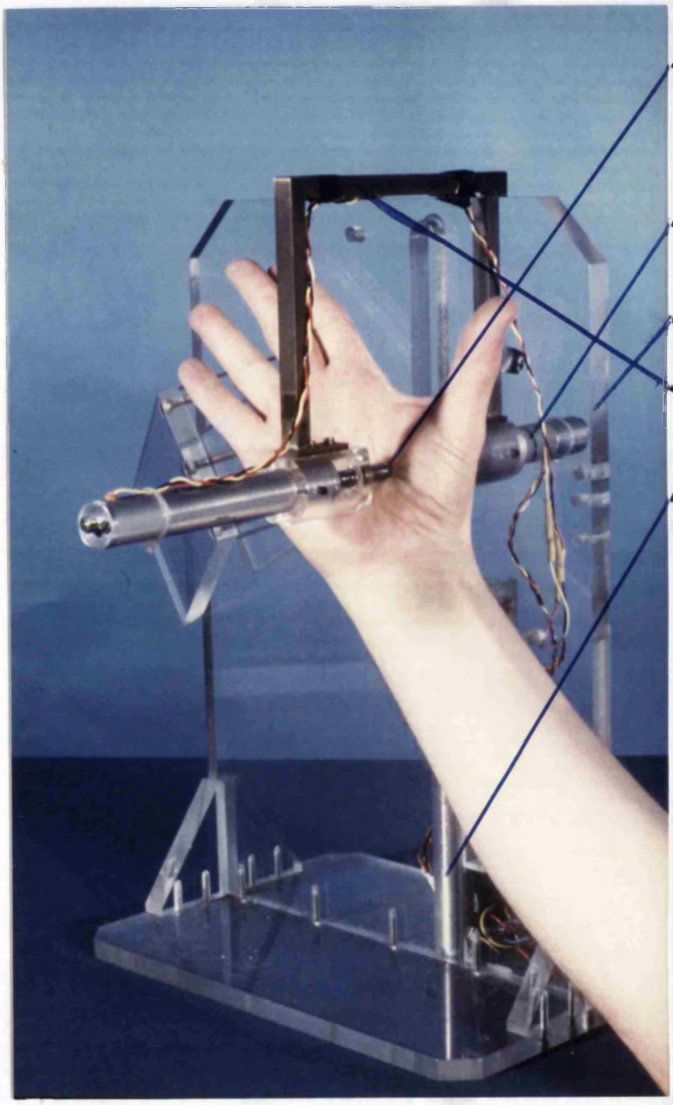
oscilloscope, a Nicolet 4094 oscilloscope, or on a personal computer using the Nicolet pc3la computer programme. Records could be transferred between the 3091 and the 4094 or pc3la programme. Maximal relaxation rate (MRR) was measured using either a differentiating programme available on the Nicolet 4094 or via the pc3la programme, and normalised by the maximum force exerted, and had the units s^{-1} (equivalent to percentage force loss in 10 ms.).

2.4 CSA estimation

CSA estimation was made with the aid of a hand-profile measuring apparatus (Fig 4).

A point was marked on the dorsal aspect of the subject's hand at the angle formed by the 1st and 2nd metacarpals. A point was marked on the palmar aspect of hand directly opposite the first point marked. Two lines were drawn from the two points marked to the midpoint of the web between the 1st and second metacarpal. The thickness of the hand along the plane of this line was measured by the difference in the outputs of a pair of (horizontally-mounted) linear potentiometers. The ends of the potentiometer shafts are held by springs against the two surfaces of the hand, and are fixed in a frame which can be moved vertically over the hand, while its position is

Fig. 4. Hand profile - measuring apparatus



Starting point of scan: the angle formed by the first and second metacarpals.

Spring-loaded linear potentiometers, measuring hand thickness.

Perspex frame.

Frame, which is moved vertically.

Potentiometer which monitors vertical movement of potentiometer--holding frame.

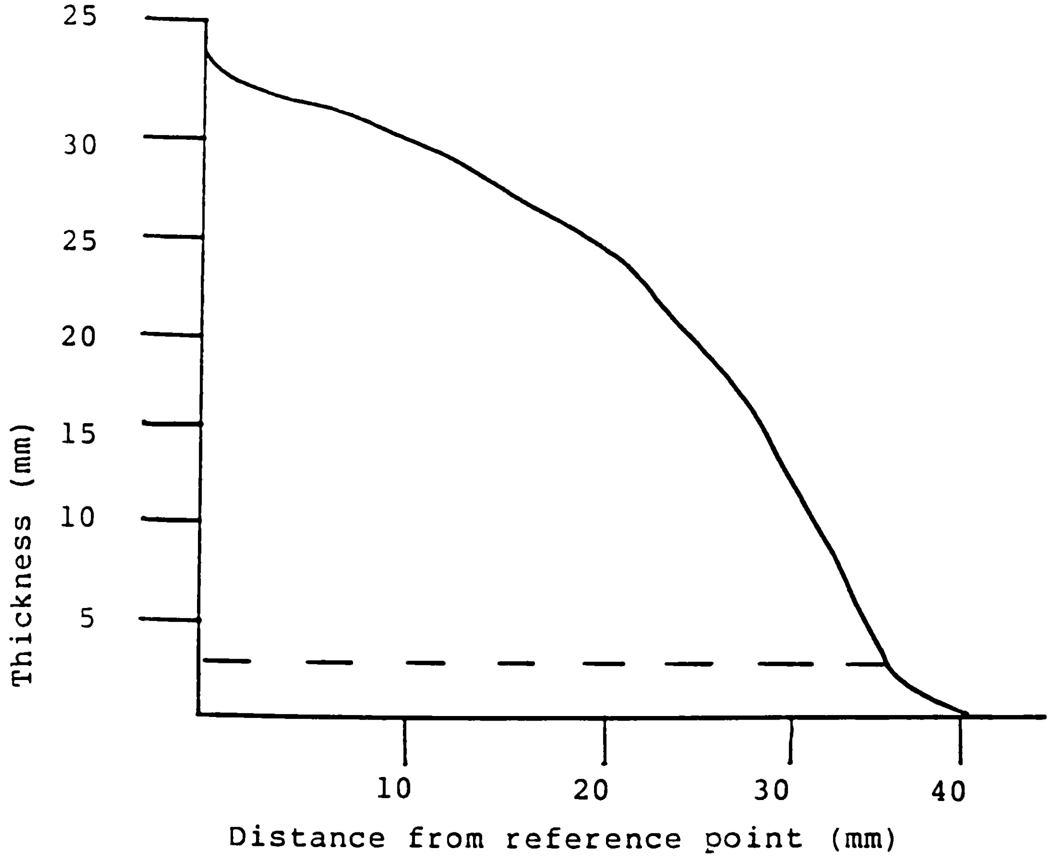
monitored by a third (vertically-mounted) potentiometer. An X-Y plot of thickness against distance moved thus represents a profile of the hand (Fig. 5). In Figure 5, the point of inflexion of the curve representing hand profile is taken to be the point at which the horizontally-mounted potentiometers pass from muscle to the non-muscular tissue of the web between thumb and first finger. The area under the (dashed) line drawn from the point of inflexion is therefore disregarded in muscle CSA estimation.

An anatomical dissection of a cadaver hand through this plane confirmed that the results of these measurements should approximate to the cross-sectional area of adductor pollicis together with part of the first dorsal interroseous.

Three profiles were obtained for each subject, the subject removing the hand from the apparatus between each measurement.

Data was collected and stored either on a Nicolet 3091 portable oscilloscope, a Nicolet 4094 oscilloscope, or on a personal computer using the Nicolet pc3la computer programme. Areas could be measured on the Nicolet 4094, which has an integrating programme, or using an extended Nicolet pc3la programme.

Fig. 5. Profile of hand cross-section.



The area above the broken line is taken to represent the area of adductor pollicis. The area below the broken line represents skin and subcutaneous fat.

METHODS

PART B: Comparison of muscle cross-sectional areas obtained from CAT and n.m.r. images with those obtained using the potentiometer rig.

2.5 General methods

Measurements of muscle cross-sectional area were made on young, healthy subjects, through the same plane as was used for the potentiometer CSA measurements, using computer-assisted tomography (CAT) (at St. Helen's Hospital, Hastings), and n.m.r imaging (at University College Hospital, London). Of 14 subjects, 12 were measured using both n.m.r imaging and potentiometry. Of the above 12, 2 (SB and DN) were also, on an earlier occasion, measured by CAT and potentiometry. Two subjects (RW and CR) were measured using CAT and potentiometry alone.

A comparison was made between the CSA measurements made in this fashion, and those obtained by use of the potentiometer rig. This was done with the aim of validating the potentiometer method of AP muscle CSA estimation.

The CAT and n.m.r. scans were carried out with the subjects' hands held in a perspex brace in a such a position that scanning was carried out in the same plane as the 'sweeps' made during estimations made using the potentiometer rig.

The operation of the CAT scanner was carried out by radiology technicians, the operation of the n.m.r. was carried out by Dr. E. Cady. The measurement of muscle CSA's from the CAT and n.m.r. images, and the subsequent processing of the data obtained, was carried out by the author.

METHODS

PART C: Muscle parameter measurements in the elderly

2.6 Subjects

21 relatively healthy elderly subjects were recruited (age range 75-94 years, mean age 80.5 years, 7 male, 14 female), from those attending a Day Centre in Hastings, (The fact that the Day Centre subjects were known to social services implies a degree of frailty, though subjects with clinical disability were excluded). Subjects were also recruited from a G.P.'s age-sex register.

Subjects were examined prior to inclusion in the study by the geriatrician S.A. Bruce, and those with specific muscle diseases, osteomalacia, pain or stiffness of movements of the thumb or specific wasting of the hand muscles, cardiovascular or thyroid disease were excluded, as were those taking regular medication likely to affect muscle function or motivation.

A control group of twenty seven normally nourished healthy subjects (age range 18 - 39 years, mean 26 years, 10 male, 17 female) was used (c.f 2.1).

2.7 Methods

MVF and CSA of adductor pollicis were measured as described in 2.3 and 2.4.

METHODS

PART D: Strength training of adductor pollicis

2.8 Subjects

Subjects were four healthy adult volunteers (1 male, 3 female, aged 22-32), the author, a friend of the author, and two members of the physiotherapy department of St. Helen's hospital, Hastings.

2.9 Training programme

The non-dominant hand was trained (this was the left hand in all subjects). The dominant hand served as a control. The length of the training period for each subject was determined to some extent by their work committments. TJL trained for 28 days; MPS for 29 days, DAN for 30 days, and UKN trained for 31 days. All four subjects trained once a day, 5 days per week. Testing was carried out using a dynamometer as described in 2.3. and illustrated in Fig. 2.

Training was carried out using a piece of apparatus consisting of a 50 ml. plastic syringe (with a graduated scale inscribed on its barrel) modified by the insertion of a short piece of dowel inserted crosswise through holes drilled in the barrel of the syringe and by the cushioning of the top of the plunger by a foam pad 'saddle'. The subjects grasped the crosspiece with his/her fingers, with the crosspiece lying in the fold created by the flexion of the fingers at the metacarpophalangeal joints, the part of the syringe barrel distal to the crosspiece plying between the second and third fingers. The subject's thumb being fully abducted, the foam 'saddle' nestled into the base of the thumb. The syringe barrel was filled with water and a little air. This enabled the syringe plunger to be depressed 2 - 5 mm or so when the subject performed an MVF in training: the greater the contraction, the more the plunger depressed; providing the subject with a means of visually assessing the strength of his/her contractions. (The minimal nature of the plunger depression ensured the training contractions were close to isometric.)

The training regime consisted of 3 sets of 10 maximal contractions, each contraction being held for 2 seconds, performed at a frequency of $10.\mathrm{min}^{-1}$, controlled by verbal signals. A one minute rest period was left between each set.

2.10 Measurement of muscle strength

Both hands were tested prior to training, followed by sessions at roughly 9, 21 and 36 days into the training (DAN and MPS were not tested at 9 days: the work commitments of subjects occasionally made it neccessary to vary the testing times. This variation, though undesirable (because it could possibly introduce a source of error into the measurements), was unavoidable.

The testing procedure consisted of 9 MVCs. The records were collected, stored and measured as described in 2.3.

2.11 Measurement of Muscle CSA

Both hands were tested prior to training, followed by sessions, as in 2.9.

The testing procedure consisted of 3 hand profiles. The records were collected, stored and measured as described in 2.4.

The coefficient of variation of the MVC measurement (dominant and non-dominant hands) at each time of testing was found to range from 2.54% - 20.27%, mean 8.37%. The variation for CSA measurement (dominant and non-dominant hands) at each time of testing ranged from 0.64% - 13.18%, mean 4.38%.

A study was carried out previously to the present study, using the same apparatus, indicated that there appeared to be a small day-to-day variation in MVF measurements (2%), but no detectable day-to-day variation in CSA measurements.
(Personal communication, Dr. S. Phillips).

METHODS

PART E: An investigation of adductor pollicis force and cross-sectional area in a group of experienced fencers

2.12 Subjects

The purpose of the present study was to investigate the force and cross-sectional area characteristics of adductor pollicis muscle in experienced competitive fencers. This was intended as a study preliminary to an intended (additional) adductor pollicis training study.

Fencing is a unilateral sport, the handle, or 'grip' of the fencing foil being held in a pinch grip between forefinger and thumb, usually in the dominant hand. The foil is manipulated by small movements of the forefinger and thumb, with assistance from the remaining fingers. The muscular effort needed to hold and wield a rapidly moving foil during a bout is considerable, and a large proportion of this work is isometric adduction of the thumb. It was thought therefore that the adductor pollicis of a fencer's fencing hand might be expected to be isometrically better trained than the adductor pollicis of the non-fencing hand. This state of training might be reflected in changes in MVF and/or CSA (c.f. 1.4).

Subjects were 7 healthy adult volunteers (5 male, 2 female, aged 22-47 years, mean 31 years), all competitive fencers of 2 or more years standing, accustomed to training on one or more evenings per week throughout the year. All were members of Bethnal Green Fencing Club.

2.13 Force measurement

MVF of the AP of both the fencing and non-fencing hand were measured. In all subjects, the fencing hand was the dominant hand. The equipment used was as described in 2.17. Records were collected, stored and measured as described in 2.3.

2.14 CSA estimation

CSA estimates of fencing and non-fencing hands were collected, stored and measured as described in 2.4.

The coefficient of variation of the MVF measurements (fencing and non-fencing hands) was found to range from 2.1 - 7.5%, mean 4.84%. The variation for CSA measurement (fencing and non-fencing hands) ranged from 0.51 - 9.3%, mean 3.07%.

METHODS

PART F: Adductor pollicis activation in the elderly

2.15 General Methods

Measurements of MVF and CSA in the elderly indicated that the elderly are able to exert less MVF/CSA in their adductor pollices than are young individuals (c.f. 3.5). This is either because the elderly muscle is intrinsically weaker than young muscle, or because the muscle is not fully activated in the elderly, either because of a lack of subject motivation or reflex inhibition.

The main purpose of the present study was to investigate the degree of activation of elderly adductor pollicis during an MVC, by means of electrical stimulation. The secondary purpose was to determine the specific force of AP muscle in a group of fit elderly using the new, improved force transducer (c.f. 2.17).

2.16 Subjects

Maximum voluntary force and cross-sectional area (MVF/CSA) of adductor pollicis were compared in groups of young (19-47 years, mean 28 years, 15 male, 13 female, n=28) and elderly (69-84 years, mean 80 years, 6 male, 5 female, n=11) subjects.

Young subjects were recruited from staff and students of University College, London (this is not the same group as used previously [c.f. 2.6], though some individuals are contained in both groups), and from the membership of a fencing club (c.f. 2.12).

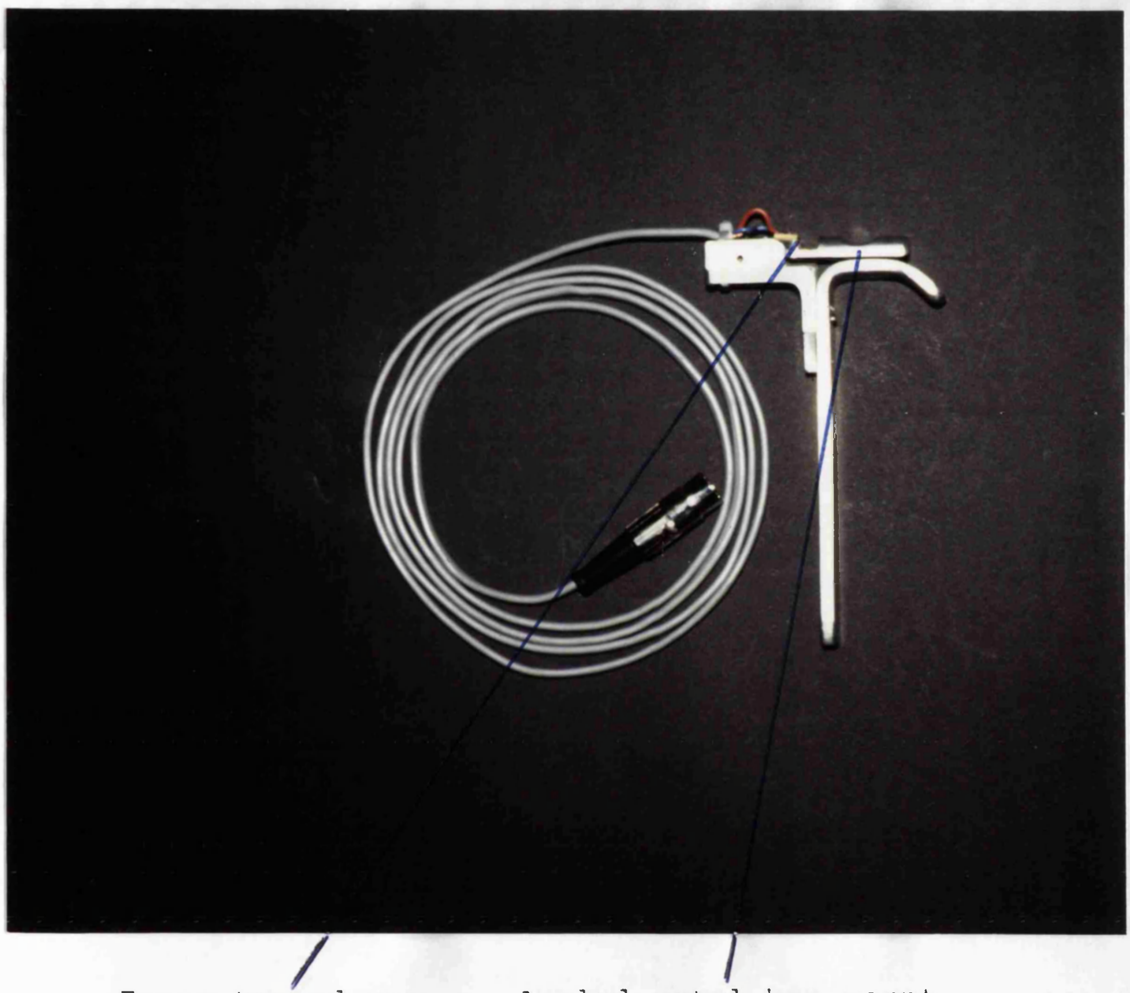
Elderly subjects were recruited from retired staff of University College, London (still active in their respective fields) and their relatives, and from a fitness club in London. As in the earlier study of adductor pollicis function in the elderly, subjects with pain or stiffness of movements of the thumb or specific wasting of the hand muscles were excluded as were those with cardiovascular, generalised neuromuscular, or thyroid disease, or those taking regular medication likely to affect muscle function or motivation. In addition, a questionnaire modified from a Department of Health and Social Security questionaire (Wickham et al., 1989) was used to acces both health and activity levels of the elderly subjects. These were analysed by the geriatrician S.A. Bruce, and on this basis subjects were selected as being fully active outdoors (Wickham et al., 1989).

2.17 Force and CSA measurement

CSA was measured as previously described (c.f 2.4).

The apparatus for measuring force had been improved since, as noted elsewhere (c.f 4.10), the original apparatus recorded some contribution from the long

Fig. 6. Bar transducer



Force transducer. Angled metal bar mount.

Fig. 7. Bar transducer in use.

Force transducer mounted on bar, which is wedged between the bases of the first and second netacarpals

Angled metal bar mount.

flexors of the fingers. The apparatus used in the present study was in the form of a force transducer mounted on an angled metal bar (Fig. 6). In use (Fig. 7), the bar is wedged between the bases of the proximal carpal bone of the thumb and the metacarpal bone of the index finger. The fingers and the interphalangeal joint of the thumb were held maximally extended during the measurements. The subjects were asked to squeeze the bar as hard as possible against the metacarpal of the index finger. Other than this equipment change, the method used to measure and record MVCs was as previously described (c.f. 2.3). For each subject the MVF is a mean of up to 9 MVCs. The CSA is a mean of 2 - 3 measurements.

2.18 Testing for full activation

For the testing of full activation, twitch interpolation was used. This is a well established technique (Merton, 1954; Belanger and McComas, 1981; Gandevia and McKenzie, 1985; Rutherford et al., 1986). The technique relies upon the fact that the size of the twitch response that is recorded after a muscle has received a single electrical shock to its motor nerve depends on the degree of activation of that muscle at the time that the shock is applied. When there is no voluntary force being applied, the twitch height is maximal; as the proportion of voluntary force is increased the superimposed twitch height decreases; as the muscle approaches full activation the twitch height approaches zero. This method is painless, the subject usually experiencing only slight discomfort. The alternative method of establishing full activation, comparison of voluntary with maximally stimulated tetanic contractions, is considerably painful, and less acceptable to subjects, particularly, one assumes, elderly subjects.

Subjects were advised initially of the nature of the stimulation, and what they might expect to experience.

A small (moistened) pad electrode was strapped, over the course of the ulnar nerve, on the medial anterior surface of the forearm 15 -20 cm. proximal to the wrist crease.

Stimulus frequency was set at 1 Hz.

Correct positioning of the second (button) electrode was determined by setting stimulus strength at a level sufficient to acheive a series of AP twitches and moving the second (moistened) electrode around, close to the wrist crease (proximal to the first electrode) until the twitch seemed largest. The second electrode was then strapped in place.

Minimum stimulus strength needed to achieve supramaximal stimulation was determined by positioning the subject's hand on the force transducer, and gradually increasing stimulus strength until no increase was apparent in twitch size as viewed on the oscilloscope screen. The stimulus strength was then increased slightly, to allow for any inadvertant change in electrode positioning.

Supramaximal twitches were imposed on voluntary contractions at 0, 25, 50, 75, and 100% of subject's MVF.

The pulses used were of 50μs duration, at a frequency of 1 Hz.

RESULTS

PART A: Effect of subnutrition on normalised muscle force and relaxation rate

3.1 Force/cross sectional area

The mean coefficient of variation for the force measurements and the CSA measurements on any one subject in the control group was 2.2% and 3.6% respectively.

The area measured by this method correlates well with measurements of muscle CSA obtained from computer-assisted tomography (CAT) and n.m.r. images through the same plane (c.f. 3.4).

The results of force and cross sectional area measurements for the 27 normal subjects are shown in Table 1. The results, combined with 20 force/CSA measurements taken during a pilot study which preceded the present study (Bruce et al., 1986b), are displayed graphically in Fig. 8. The regression line for the 27 controls is shown, and the pilot study observations are evenly scattered about it. Although the pilot study force records were, after appropriate calibration, comparable to the force records in the present study, they were obtained using a different force transducer (Bruce et al., 1986a) and so are not included in the present study. They are included in Fig. 8 in order to provide a general comparison of the present observations with previous observations.

The results of force and cross-sectional area measurements for the nine subnourished patients are shown

Table 1: MVF & CSA for 27 normally - nourished subjects

Name	Sex	Age	Force (N)	CSA (mm^2)	Force/CSA (N/mm^2)
LD	F	20	96	206	0.47
MS	F	20	94	222	0.42
MP	M	31	130	262	0.50
CT	F	26	109	307	0.36
SS	F	19	132	308	0.43
DP	F	25	132	321	0.41
C FR	F	23	85	323	0.26
AC	F	25	141	323	0.44
TM	F	27	126	327	0.39
UN	F	20	115	346	0.33
GC	F	39	146	354	0.41
JS	F	18	137	367	0.37
LH	F	20	125	383	0.33
DI N	F	38	155	388	0.40
SP	F	27	111	400	0.28
C FY	F	38	117	418	0.28
DR	M	34	157	434	0.36
MW	M	31	163	435	0.37
RO-M	F	18	106	441	0.24
KS	M	24	197	451	0.44
OR	F	26	157	534	0.29
YC	M	30	199	558	0.36
PE	F	23	205	588	0.35
DN	M	30	234	642	0.36
KH	M	19	281	654	0.43
MC	M	20	214	656	0.33
TC	M	31	251	780	0.32
Number		27.00	27.00	27.00	27.00
Range		21.00	196.00	574.00	0.26
Mean		26.00	152.41	423.26	0.37
S.D.			50.58	144.00	0.06
CV			33%	34%	18%

in Table 2.

The combined results (27 controls and nine subnourished) are displayed graphically in Fig. 9.

There is no significant difference between the force/unit CSA developed by the control group and that developed by the subnourished group, though the subnourished are generally weaker than the controls. Two of the patients with Crohn's disease fall considerably outside the 95% confidence limits. These individuals are discussed in the discussion section (c.f. 4.1).

It can be seen that the regression lines in Figs. 8 and 9 show positive intercepts. A likely explanation for this is that there are random errors in the values of 'x'.

3.2 Force/height

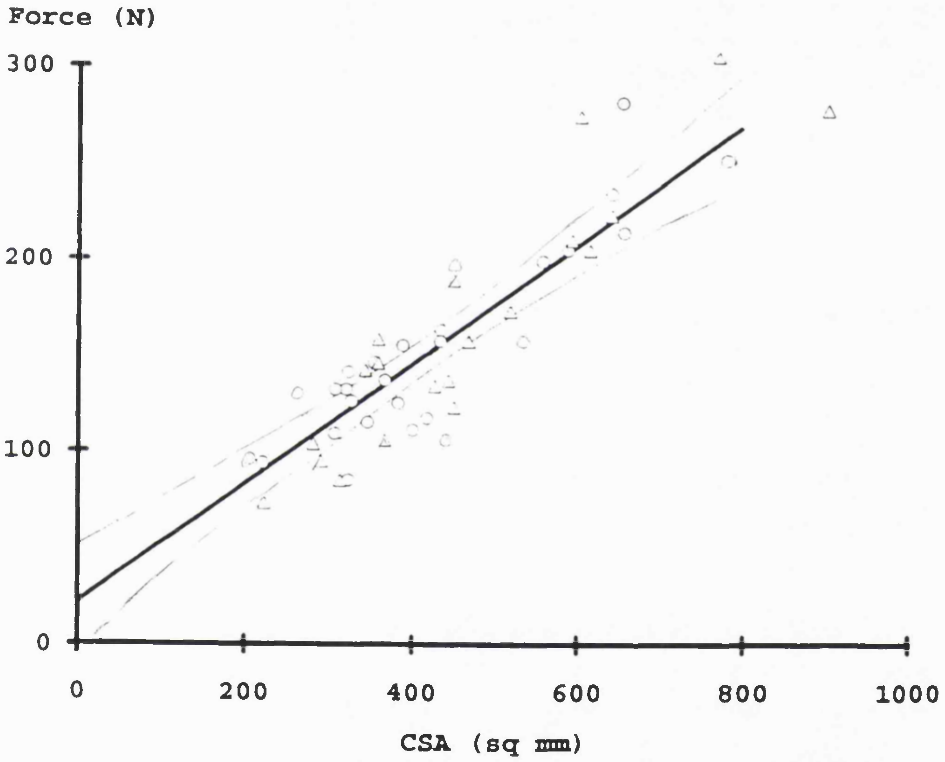
The subnourished are all below 90% Ideal Body Weight for their height (c.f. 2.1). This is reflected in the relationship of their muscle force and their height measurements. The results of force and height measurements for the 27 controls and nine subnourished are shown in Tables 3 and 4 respectively. The results are displayed graphically in Fig. 10. The subnourished are weaker relative to their height than are the controls. This finding is addressed further in the discussion section.

There is a significant correlation between force and height in the control group, but not in the subnourished group. This is probably due to the effect of the greater range of heights in the control group (range:

TABLE 2: MVF & CSA for 9 subnourished patients

Name	Sex	Age	Force (N)	Area (mm^2)	Force/CSA (N/mm^2)
KM	F	22	80	189	0.42
CE	F	53	43	266	0.16
SA	M	31	108	267	0.40
SL	F	19	108	287	0.38
KS	M	27	101	288	0.35
JM	M	19	143	370	0.39
PC	M	54	134	402	0.33
ME	M	21	153	447	0.34
LH	F	21	79	460	0.17
Number		9.00	9.00	9.00	9.00
Range		35.00	110.00	271.00	0.26
Mean		30.75	105.44	330.67	0.33
S.D.			34.94	92.82	0.10
CV			33%	28%	29%

Fig. 8. MVF / CSA, 27 normal subjects and 20 pilot study observations.



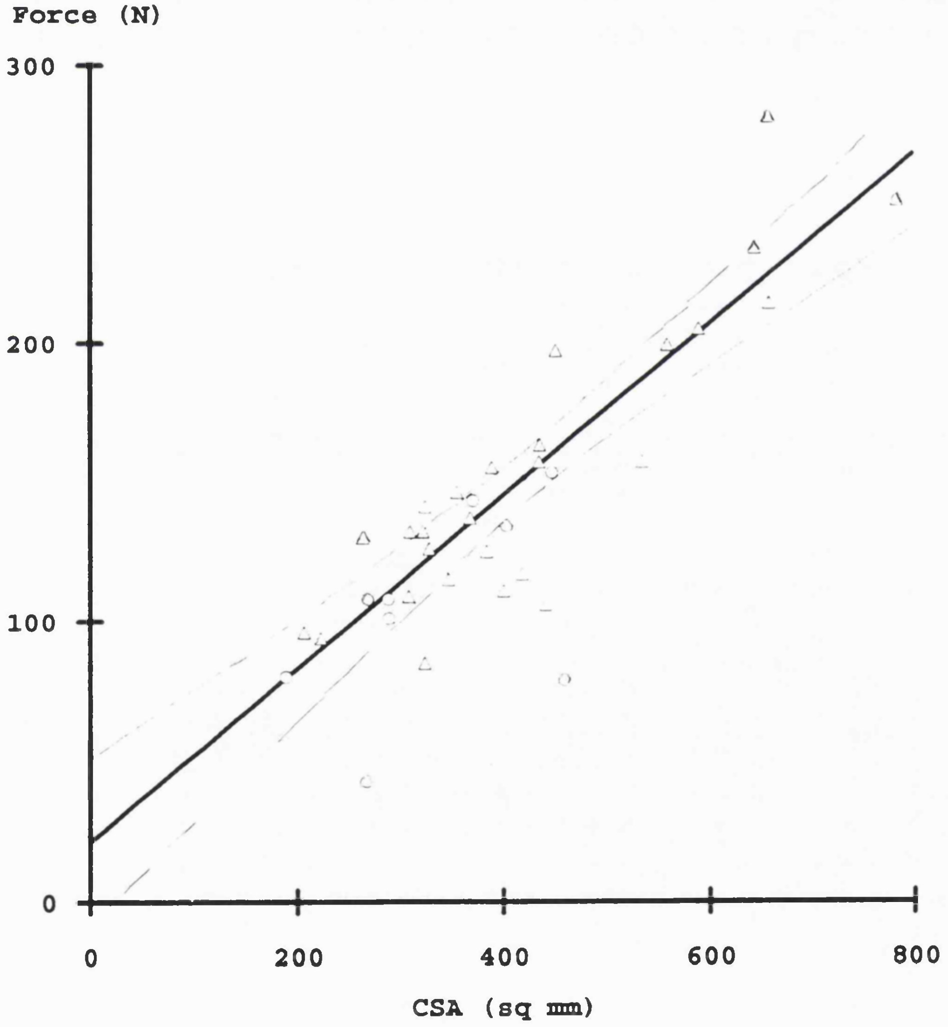
triangles = pilot study observations

circles = normal subjects

continuous thick line = normal subject's regression line. (r=0.88, P<0.001).

continuous thin lines = 95% confidence limits for normal subjects' regression line.

Fig. 9. MVF/CSA, 27 controls and 9 subnourished.



triangles = controls

circles = subnourished

thick solid line = regression line for 27 controls. (r=0.88, P<0.001).

thin solid lines = 95% confidence limits for control observation's regression line

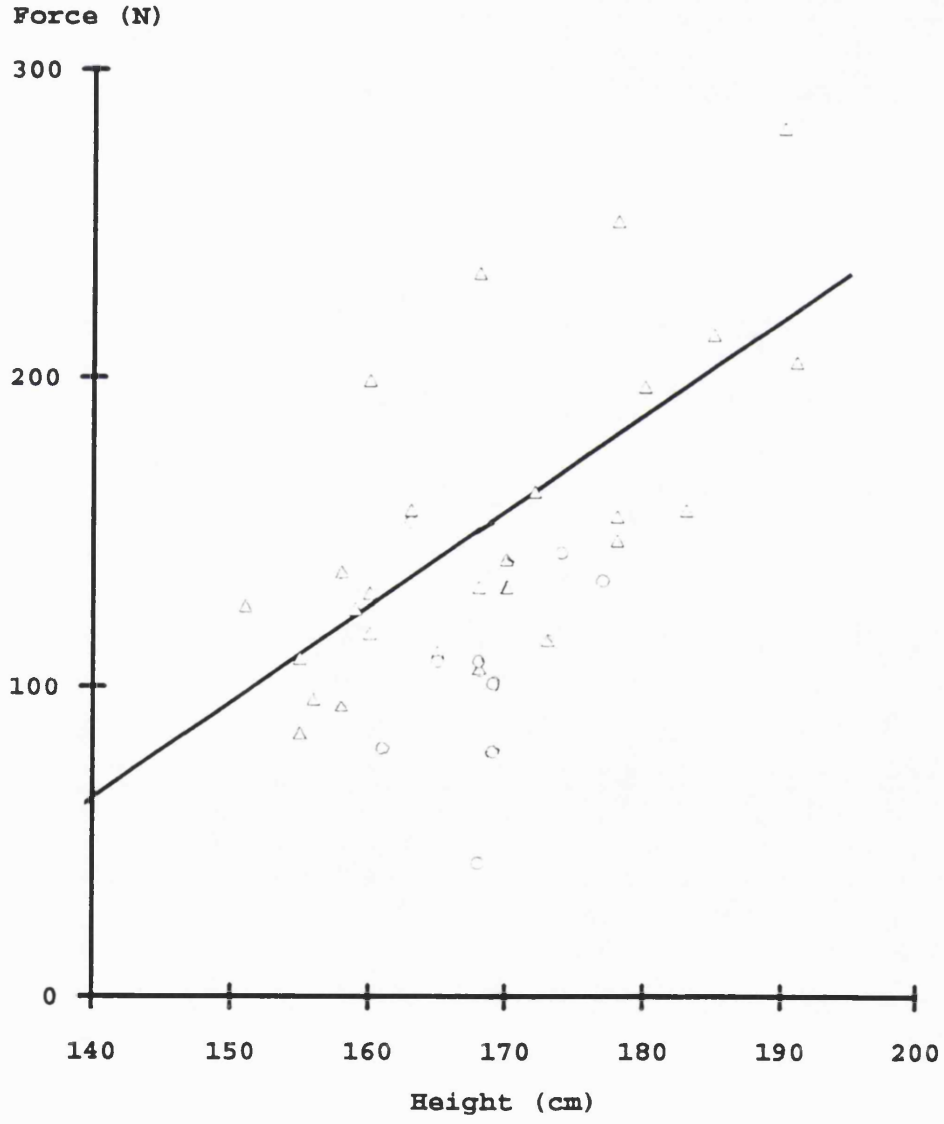
TABLE 3: MVF & Height for 27 controls

Name	Force (N)	Height (cm)	Force/Height (N/cm)
TM	126	151	0.83
CT	109	155	0.70
C FR	85	155	0.55
LD	96	156	0.62
JS	137	158	0.87
MS	94	158	0.59
LH	125	159	0.79
YC	199	160	1.24
MP	130	160	0.81
C FY	117	160	0.73
OR	157	163	0.96
SP	111	165	0.67
DN	234	168	1.39
DP	132	168	0.79
RO-M	106	168	0.63
AC	141	170	0.83
SS	132	170	0.78
MW	163	172	0.95
UN	115	173	0.66
TC	251	178	1.41
GC	146	178	0.82
DI N	155	178	0.87
KS	197	180	1.09
PE	205	181	1.13
DR	157	183	0.86
MC	214	185	1.16
KH	281	190	1.48
Number	27.00	27.00	27.00
Range	196.00	39.00	0.93
Mean	152.41	168.22	0.90
S.D.	50.58	10.63	0.26
CV	33%	6%	29%

TABLE 4: MVF & Height for 9 subnourished patients

Name	Force (N)	Height (cm)	Force/Height (N/cm)
KM	80	161	0.50
CE	43	163	0.26
JM	143	165	0.87
SA	108	168	0.64
ME	153	168	0.91
KS	101	169	0.60
LH	79	169	0.47
SL	108	174	0.62
PC	134	177	0.76
Number	9.00	9.00	9.00
Range	110.00	16.00	0.65
Mean	105.44	168.22	0.62
S.D.	34.94	5.02	0.20
CV	33%	3%	33%

Fig. 10. MVF/height, 27 controls and 9 subnourished.



triangles = controls

circles = subnourished

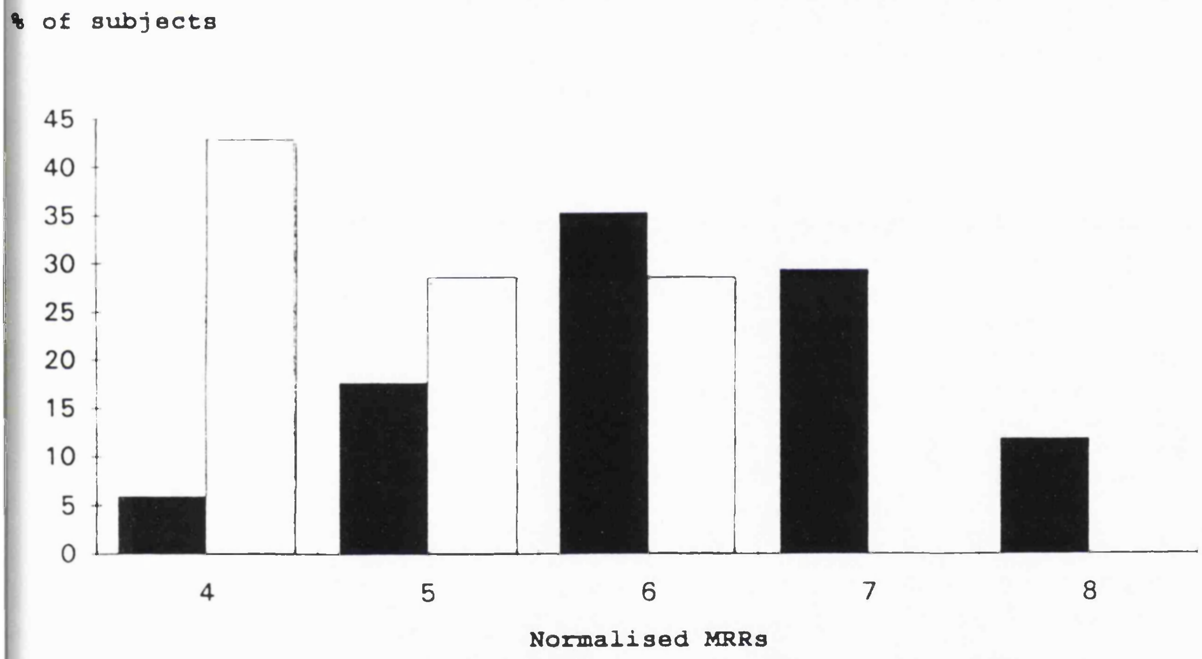
solid line = regression for controls (r=0.68, P<0.001).

151 - 191 cm, mean 168 cm.) than in the subnourished group (range: 161 - 177 cm., mean 168.3 cm.), combined with the variable degree of subnutrition in the subnourished group (range: 64% - 88.8% Ideal Body Weight).

3.3 Maximum relaxation rate.

MRR was measured for 17 of the control group and seven of the subnourished patients. The normalised MRR in the control group was 6.62 ± 0.26s^{-1} (mean + SEM, range 4.9-8.1s^{-1}). In the subnourished patients the value was 5.52 ± 0.38s^{-1} (range 4.0-6.7s^{-1}). Relaxation was, therefore, significantly lower in the latter group ($P<0.001$). These results are shown in Table 5 (control MRRs) and Table 6 (subnourished MRRs), and displayed graphically in Fig. 11.

Fig. 11. MRR, 17 controls and 7 subnourished.



(equivalent to % loss of MVF in 10ms.)

black columns = controls

white columns = subnourished

TABLE 5: Maximum Relaxation Rates --Controls (% loss of force/10 ms.)

Name	MRR
LH	4.9
TC	5
C FR	5.1
AC	5.3
KH	6
MP	6.2
TM	6.4
UN	6.7
YC	6.8
SP	6.9
MW	7.4
GC	7.5
MC	7.5
CT	7.7
KS	7.7
C FY	8
DP	8.1
Number	17
Range	3.2
Mean	6.66
S.D.	1.09
CV	16%

TABLE 6: Maximum Relaxation Rates --Subnourished (% loss of force/10 ms.)

Name	MRR
CE	4
KM	4.5
SL	4.6
KS	5.1
LH	5.4
SA	6.4
PC	6.7
Number	7
Range	2.7
Mean	5.24
S.D.	1.00
CV	19%

RESULTS

PART B: Comparison of muscle cross-sectional areas obtained from CAT and n.m.r. images with those obtained using the potentiometer rig.

3.4 General results

The results of the cross-sectional area measurements for the 14 subjects (four CAT measurements, 12 n.m.r measurements) are shown in Table 7. The results are displayed graphically in Fig. 12.

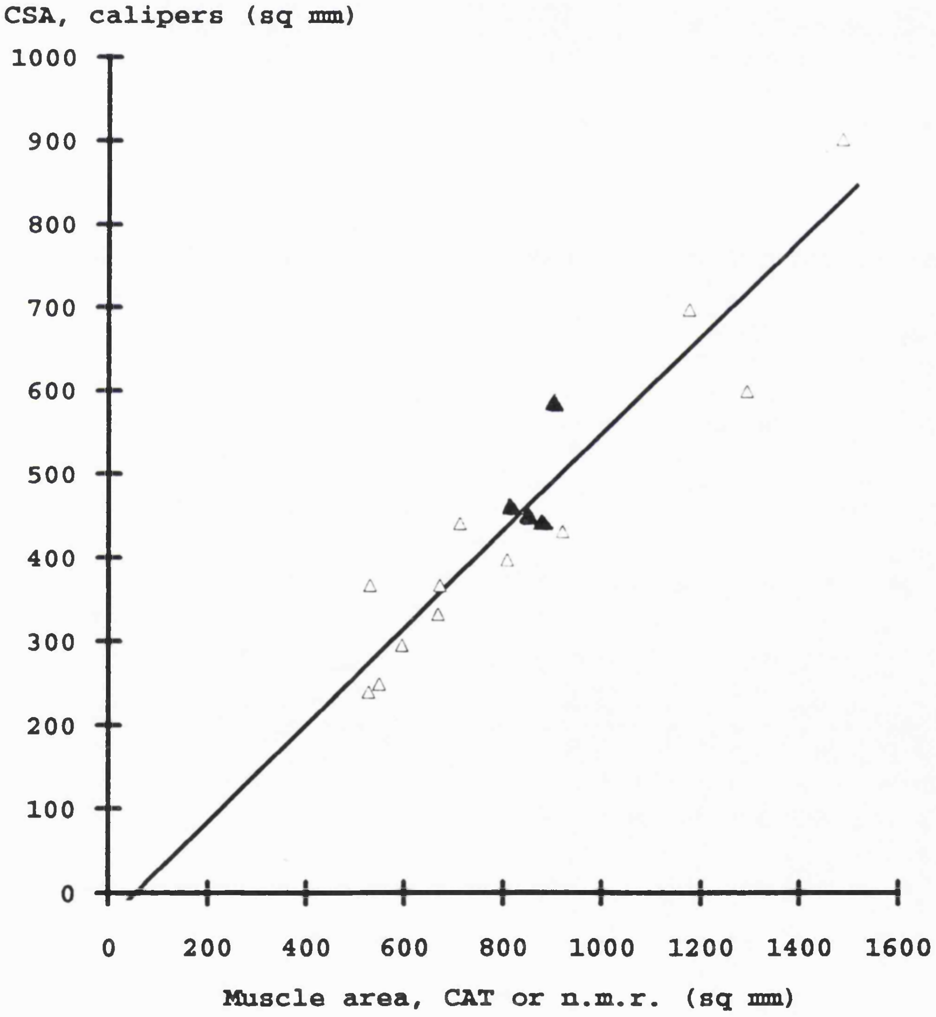
The measurements using the potentiometer rig correlate well with those obtained by CAT and n.m.r. (r=0.937).

The CSAs obtained using the potentiometer rig appears to underestimate the actual muscle CSA by 46% (mean potentiometer-obtained CSAs = 453sq. mm., mean CAT/n.m.r-obtained CSAs=836 sq. mm.). This is partly because some of the adductor pollicis is proximal to the bases of the metacarpal bones and is therefore not included in the potentiometer CSA measurements, and partly because of the slight compressing effect of the springs holding the potentiometers against the dorsal and anterior surfaces of the hand. The implications of this underestimation are discussed later (c.f. 4.4).

TABLE 7: Relationship between muscle area as measured by CAT, n.m.r, and potentiometry

		Area measurements (sq. mm.)	
Subject	N.m.r.	CAT	CSA
K E	527		239
L M	549		249
L W	594		295
C F	668		332
G C	671		366
T M	530		366
Di N	808		397
D N	921		430
S B	712		440
B B	1292		598
P E	1175		696
T C	1485		901
S B		881	440
R W		849	447
D N		814	462
C R		902	584

Fig. 12. Potentiometer-estimated CSA/CAT- & n.m.r.-measured CSA.



black triangles = CAT CSAs

white triangles = n.m.r. CSAs

continuous black line = regression line, (r=0.937, P<0.001).

RESULTS

PART C: Muscle parameter measurements in the elderly.

3.5 Force/Cross sectional area

The results for the force and cross-sectional area measurements for the 27 control and 21 elderly subjects are shown in Table 8 and 9 respectively.

The combined results are displayed graphically in Fig. 13.

Both groups show significant correlations between force and cross-sectional area (controls, $r=0.88$), elderly, $r=0.76$, $P<0.001$).

It can be seen that the elderly observations are well below those of the control group; the mean normalised force was significantly lower ($t=1.89$; $P<0.05$) for the elderly group (0.302 N/sq. mm.) than for the control group (0.368N/sq. mm.), being 82.1% of that for the control group.

3.6 Force/Height

The results for the force and height measurements for the controls and elderly are shown in Table 10 and 11 respectively. The results are displayed graphically in Fig. 14.

Both groups show significant correlations for force

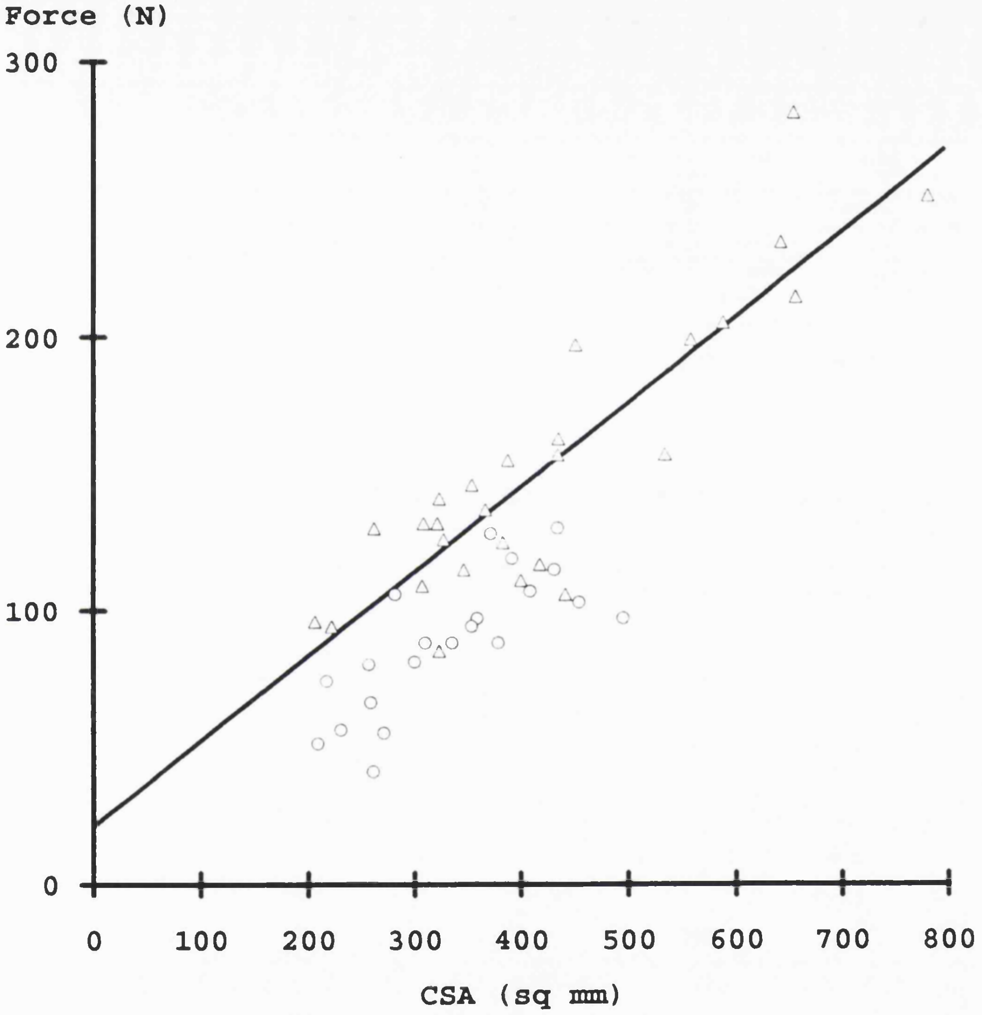
Table 8: MVF & CSA for 27 young control subjects

Name	Sex	Age	Force (N)	CSA (mm^2)	Force/CSA (N/mm^2)
LD	F	20	96	206	0.47
MS	F	20	94	222	0.42
MP	M	31	130	262	0.50
CT	F	26	109	307	0.36
SS	F	19	132	308	0.43
DP	F	25	132	321	0.41
C FR	F	23	85	323	0.26
AC	F	25	141	323	0.44
TM	F	27	126	327	0.39
UN	F	20	115	346	0.33
GC	F	39	146	354	0.41
JS	F	18	137	367	0.37
LH	F	20	125	383	0.33
DI N	F	38	155	388	0.40
SP	F	27	111	400	0.28
C FY	F	38	117	418	0.28
DR	M	34	157	434	0.36
MW	M	31	163	435	0.37
RO-M	F	18	106	441	0.24
KS	M	24	197	451	0.44
OR	F	26	157	534	0.29
YC	M	30	199	558	0.36
PE	F	23	205	588	0.35
DN	M	30	234	642	0.36
KH	M	19	281	654	0.43
MC	M	20	214	656	0.33
TC	M	31	251	780	0.32
Number		27.00	27.00	27.00	27.00
Range		21.00	196.00	574.00	0.26
Mean		26.00	152.41	423.26	0.37
S.D.			50.58	144.00	0.06
CV			33%	34%	18%

TABLE 9: MVF & CSA for 21 elderly subjects

Name	Sex	Age	Force (N)	CSA (mm)	Force/CSA (N/r
W D	F	81	51	209	0.24
F I	M	78	74	217	0.34
P B	F	79	56	231	0.24
F H	F	78	80	257	0.31
L M	F	80	66	259	0.25
M D	F	84	41	261	0.16
F EL	F	83	55	271	0.20
S D	F	84	106	282	0.38
A W	F	79	81	300	0.27
W BE	M	94	88	310	0.28
G S	F	80	88	335	0.26
V L	F	79	94	354	0.27
F EN	F	76	97	359	0.27
E E	M	78	128	372	0.34
G W	F	85	88	379	0.23
W T	M	75	119	392	0.30
W BU	M	77	107	409	0.26
G H	M	86	115	431	0.27
L R	M	81	130	434	0.30
G W	F	81	103	454	0.23
E D	F	80	97	495	0.20
Numbe		21	21	21	21
Range		19	89	286	0.21
Mean		80.86	88.76	333.86	0.27
S.D.			25.13	83.19	0.05
CV			28%	25%	19%

Fig. 13. MVF/CSA, 27 controls and 21 elderly.



triangles = controls

circles = elderly

solid line = regression line for controls (r=0.88, P<0.001).

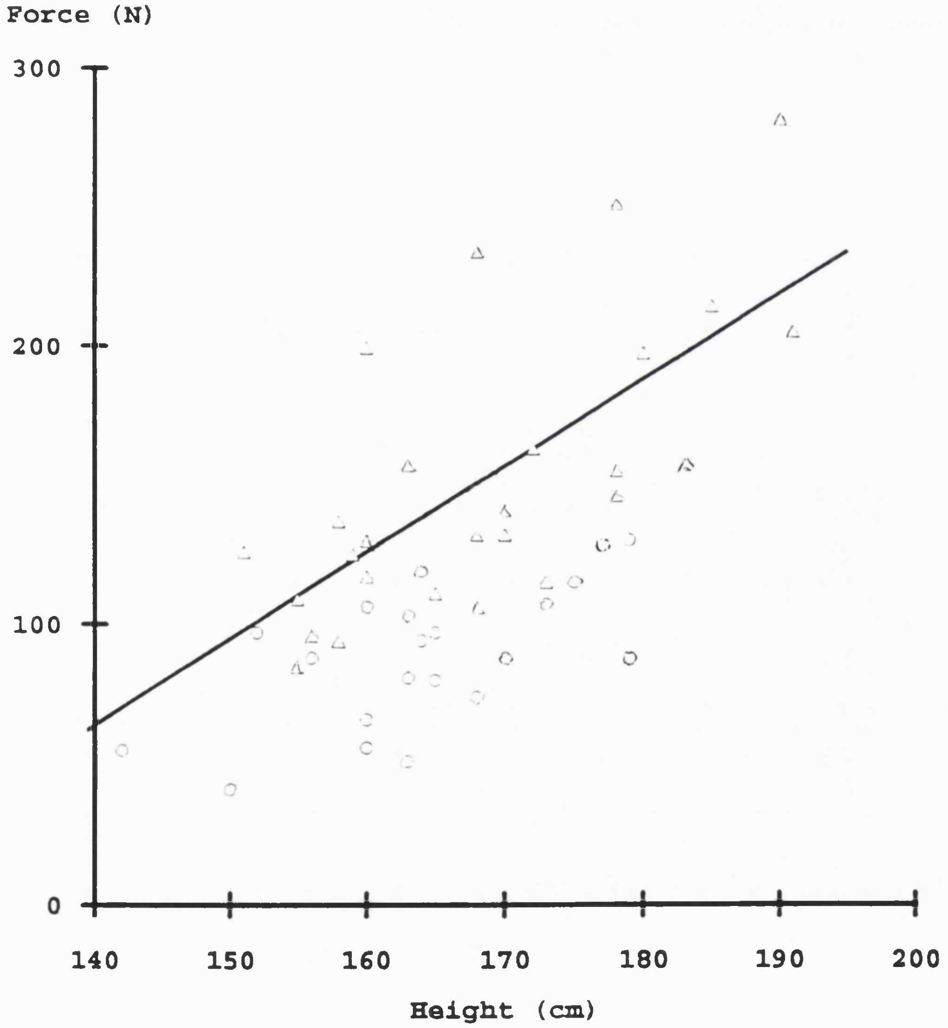
TABLE 10: MVF & Height for 27 controls

Name	Force (N)	Height (cm)	Force/Height (N/cm)
TM	126	151	0.83
CT	109	155	0.70
C FR	85	155	0.55
LD	96	156	0.62
JS	137	158	0.87
MS	94	158	0.59
LH	125	159	0.79
YC	199	160	1.24
MP	130	160	0.81
C FY	117	160	0.73
OR	157	163	0.96
SP	111	165	0.67
DN	234	168	1.39
DP	132	168	0.79
RO-M	106	168	0.63
AC	141	170	0.83
SS	132	170	0.78
MW	163	172	0.95
UN	115	173	0.66
TC	251	178	1.41
GC	146	178	0.82
DI N	155	178	0.87
KS	197	180	1.09
PE	205	181	1.13
DR	157	183	0.86
MC	214	185	1.16
KH	281	190	1.48
Number	27.00	27.00	27.00
Range	196.00	39.00	0.93
Mean	152.41	168.22	0.90
S.D.	50.58	10.63	0.26
CV	33%	6%	29%

TABLE 11: MVF & Height for 21 elderly subjects

Name	Force (N)	Height (cm)	Force/Height (N/cm)
F EL	55	142	0.39
M D	41	150	0.27
F EN	97	152	0.64
G W	88	156	0.56
P B	56	160	0.35
L M	66	160	0.41
S D	106	160	0.66
W D	51	163	0.31
A W	81	163	0.50
G W	103	163	0.63
V L	94	164	0.57
W T	119	164	0.73
F H	80	165	0.48
E D	97	165	0.59
F I	74	168	0.44
G S	88	170	0.52
W BU	107	173	0.62
G H	115	175	0.66
E E	128	177	0.72
W BE	88	179	0.49
L R	130	179	0.73
Number	21.00	21.00	21.00
Range	89.00	37.00	0.45
Mean	88.76	164.19	0.54
S.D.	25.13	9.52	0.14
CV	28%	6%	26%

Fig. 14. MVF/height, 27 controls and 21 elderly.



triangles = controls

circles = elderly

solid line = regression line for controls (r=0.68, P<0.001).

and height (controls r= 0.68, P<0.001; elderly, r=0.63, P<0.01).

The ratio of force to height in the aged is 60% that of the control group, and is significantly different to that of the control group.

Results:

Part D: Strength training of adductor pollicis

3.7 General Results

Prior to training, there was no significant difference between dominant and non-dominant hands in either muscle force or muscle CSA. Neither was there a significant difference in these factors pre- and post-training.

3.8 High specific force

Muscle force and CSA measurements for the subject's dominant and non dominant hands, both pre- and post-training, are shown in Table 12. These combined measurements, together with the Young Control observations described in 3.1, are shown graphically in Fig. 15. The observations for the training group observations are significantly above those of the Young Control group.

The protocol for testing strength and CSA and the equipment used for their measurement was identical in the Young Control Study and the present study. Nonetheless, the Training group show a greater MVF/CSA relationship than the Young Control group. Why?

Table 12: MVF & CSA measurements, pre- and post - training.

CSA of trained hand

	CSA (sq. mm)			
Subject	Pre	Post	% Change	Mean % change
MPS	295	366	24	9%
DAN	359	423	18	
UKN	313	326	4	
TJL	365	330	-10	

CSA of untrained hand

	CSA (sq. mm)			
Subject	Pre	Post	% Change	Mean % Change
MPS	293	371	27	7.5%
DAN	397	499	26	
UKN	374	362	-3	
TJL	462	371	-20	

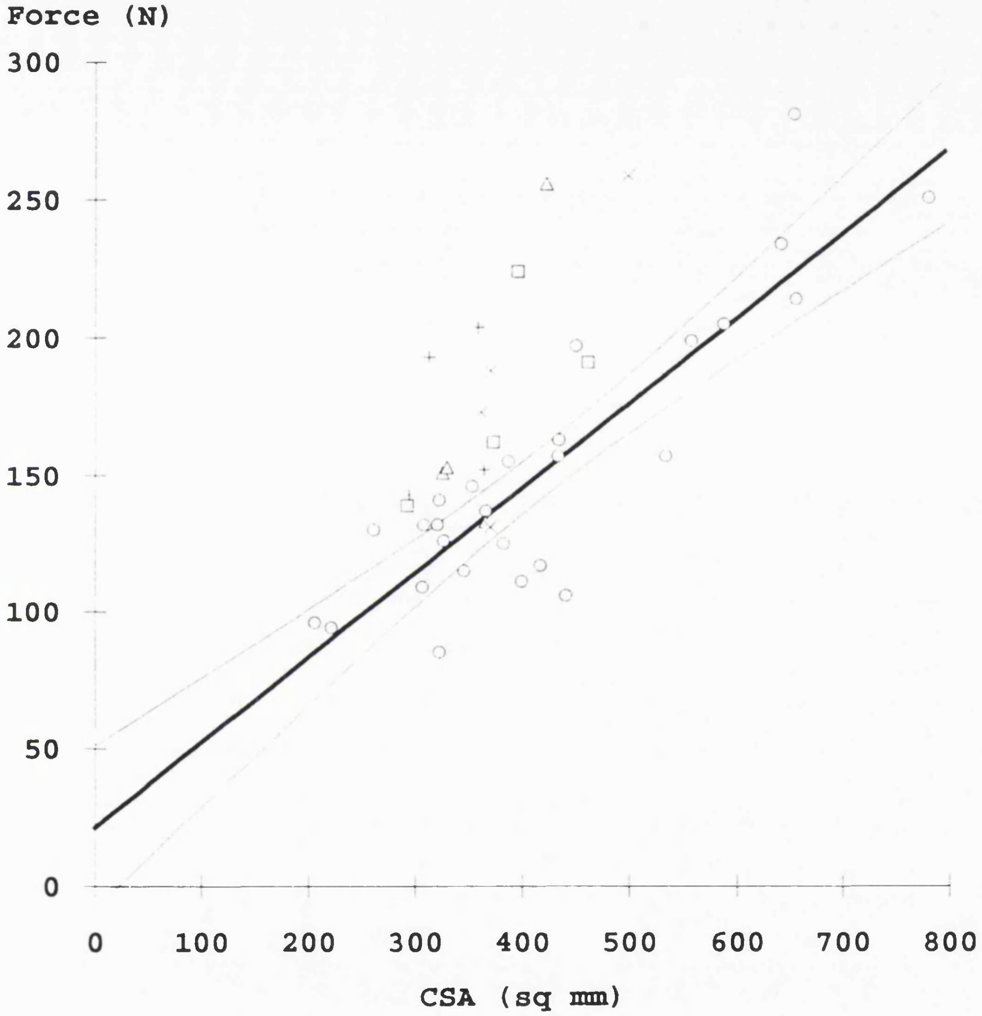
MVF of trained hand

	Force (N)			
Subject	Pre	Post	% Change	Mean % Change
MPS	143	133	-7	- 0.5%
DAN	204	256	26	
UKN	193	151	-22	
TJL	152	153	1	

MVF of untrained hand

	Force (N)			
Subject	Pre	Post	% Change	Mean % Change
MPS	139	131	-6	3.8%
DAN	224	259	16	
UKN	162	173	7	
TJL	191	188	-2	

Fig. 15: MVF / CSA, training group & young controls.



× = post-training observations, untrained hand.
△ = post-training observations, trained hand.
□ = pre-training observations, untrained hand.
+ = pre-training observations, trained hand.
continuous solid line = regression line, controls (r=0.88, P<0.001).
continuous thin lines = 95% confidence limits for the controls' regression line.

explanations are:

1. The Young Controls were not fully activating their muscle during testing, and the Trainers were. (Also, since the correlation between force and CSA was high in the Young Controls (0.88), each YC individual must have been underactivating his/her muscle to a similar degree.)

2. A learning effect has taken place in the Trainers. Prior to the taking of the baseline ('Pretest') measurements, the trainers, during their many practises with both muscle Test and Training equipment, acquired skill in the use of accessory muscles which contributed to the high force measurements found at the time of baseline tests. The learning curve must have plateaued early, since there is no significant increase in specific force subsequent to the time of the baseline tests.

3. A combination of (1) and (2) above.

It is extremely unlikely that the Trainers activated their muscle to a greater degree than the Young Controls: as mentioned above, equipment and, to a large extent, protocol, was identical in both study groups. Indeed, subsequent twitch interpolation experiments (c.f. 3.10), partly prompted by the results of the present study) carried out on a subject included in the original Young control group demonstrated that the specific force measurement obtained by this subject in the YC study was with full recruitment of adductor pollicis.

The main difference in protocol between the training and YC groups was the provision given in the Training study for practice with training and force testing apparatus prior to the taking of the baseline force measurements. In the YC study, the testing of an individual's MVC involved a single set of measurements with only two or three practise MVC's. If a learning effect is prone to occur with the force-testing apparatus, it is much more likely to occur in the well-practised Trainer group than in the relatively unpractised YC group.

RESULTS

PART E: An investigation of adductor pollicis force and cross-sectional area in a group of experienced fencers

3.9 MVF/CSA

Muscle force and CSA measurements for the fencer's fencing hands (dominant hands) and non-fencing hands (non-dominant hands) are shown in Table 13, where the difference between the fencing hand and non-fencing hand MVF, CSA, and MVF/CSA of each individual is shown expressed as a percentage difference. The combined MVF and CSA measurements are shown graphically in Fig. 16. There is no difference between the fencing (presumed trained) and non-fencing (presumed untrained) hand in terms of measured force or CSA, (and hence, no difference in terms of specific force). No training effect is evident in the fencing hand as compared to the non-fencing hand.

Fig. 17 shows the force/CSA measurements and regression line for a group of young controls (c.f 3.10), and the force/CSA measurements for the fencers. It can be seen that there is no difference between these two groups (both of which were measured using the bar-type force transducer) in terms of specific force. There is no training effect evident in either the fencing or non-fencing hand of the fencers as compared

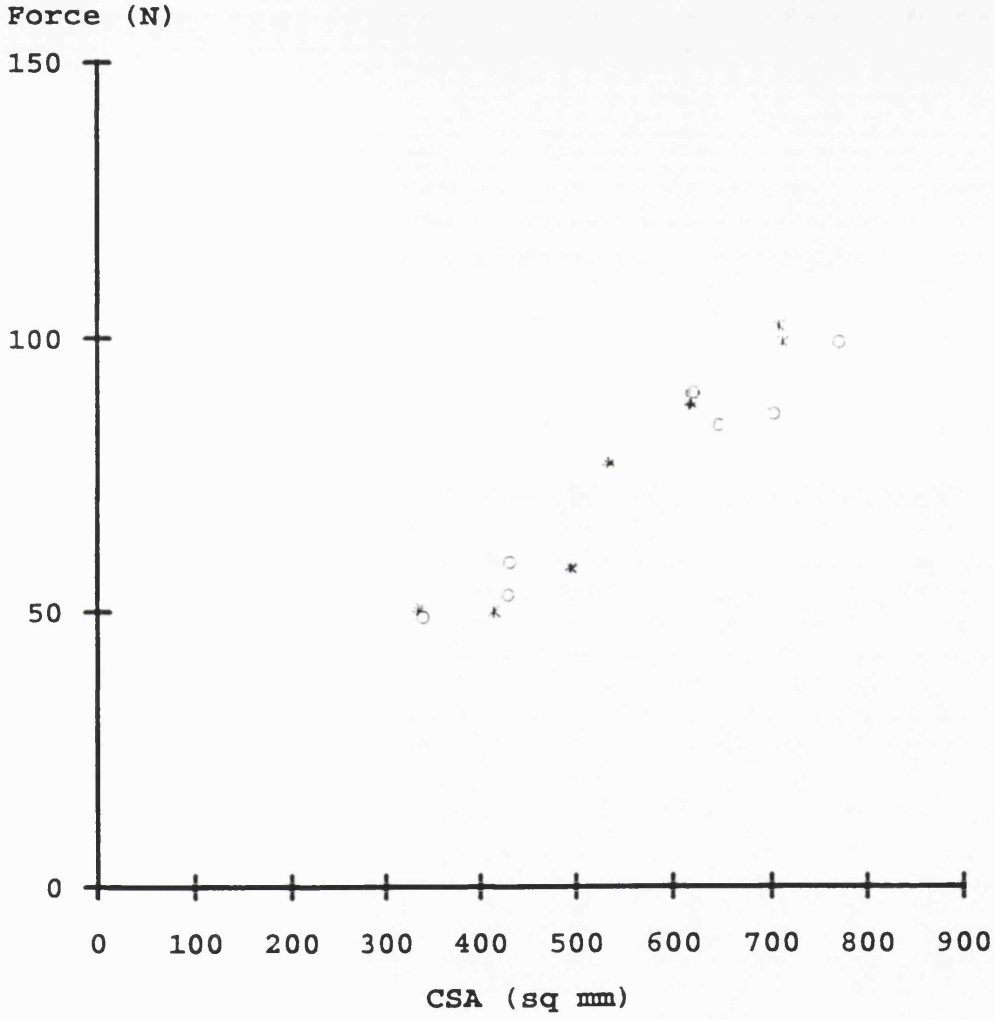
Table 13: MVF/CSA, fencing and non-fencing hands.

Name	fencing hand			non-fencing hand			fencing - non-fencing (% diff)		
	MVF	CSA	MVF/CSA	MVF	CSA	MVF/CSA	MVF	CSA	MVF/CSA
TEW	99	771	0.13	99	712	0.14	0	8	-7
EEL	86	703	0.12	102	708	0.14	-16	-0.7	-14
RUF	49	340	0.14	50	335	0.15	-2	1	-7
GLS	90	621	0.14	88	619	0.14	2	0	0
WID	53	430	0.12	58	495	0.12	-9	-13	0
KEN	84	647	0.13	77	536	0.14	9	21	-7
LOA	59	432	0.14	50	415	0.12	18	4	17

group.

These results are addressed further in the discussion (4.13 - 4.15).

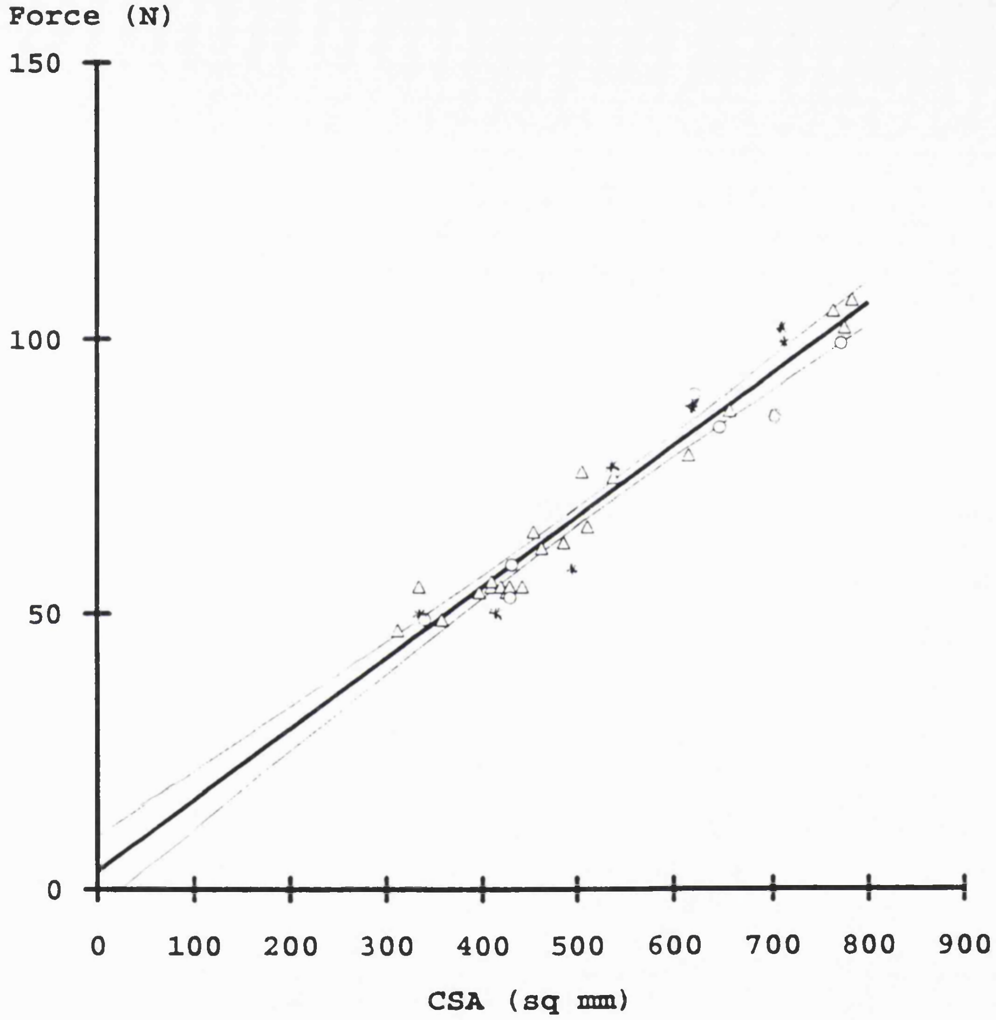
Fig. 16. MVF/CSA, fencing and non-fencing hands.



asterixes = non-fencing hand

circles = fencing hand

Fig. 17. MVF/CSA, young controls and fencers.



triangles = young controls (MVF measured with new, coathook type force transducer [c.f. 3.10].
asterixes = fencers, non-fencing hands

circles = fencers, fencing hands.

Thick solid line = regression line for controls (r=0.95, P<0.001).

Thin solid lines = 99% confidence limits for control observations.

RESULTS

PART F: Adductor pollicis activation in the elderly.

3.10 MVF/CSA

MVF and CSA measurements for the 11 elderly and 28 young controls are shown in Table 14 and Table 15 respectively and displayed together in Fig. 18. Significant correlations were found between MVF and CSA for both groups. The correlation coefficient was higher for the young group (0.95) than for the elderly group (0.61). The regression line for the elderly is significantly different to that of the young group.

3.11 Twitch interpolation

Results from twitch interpolation experiments on 8 young subjects are shown in Fig 20. It was found that correct positioning of the thumb on the pressure transducer resulted in a slight deflection, with the consequence that twitch height at 0% of MVF could not always be reliably recorded. Therefore, twitch height for each subject is presented as a proportion of twitch height at 20% of MVF (normalised twitch height), which could be determined satisfactorily. Normalised twitch height is plotted against the degree of voluntary contraction expressed as a percentage of MVF. The relationship between twitch height and voluntary force is curvilinear, as previously shown for quadriceps

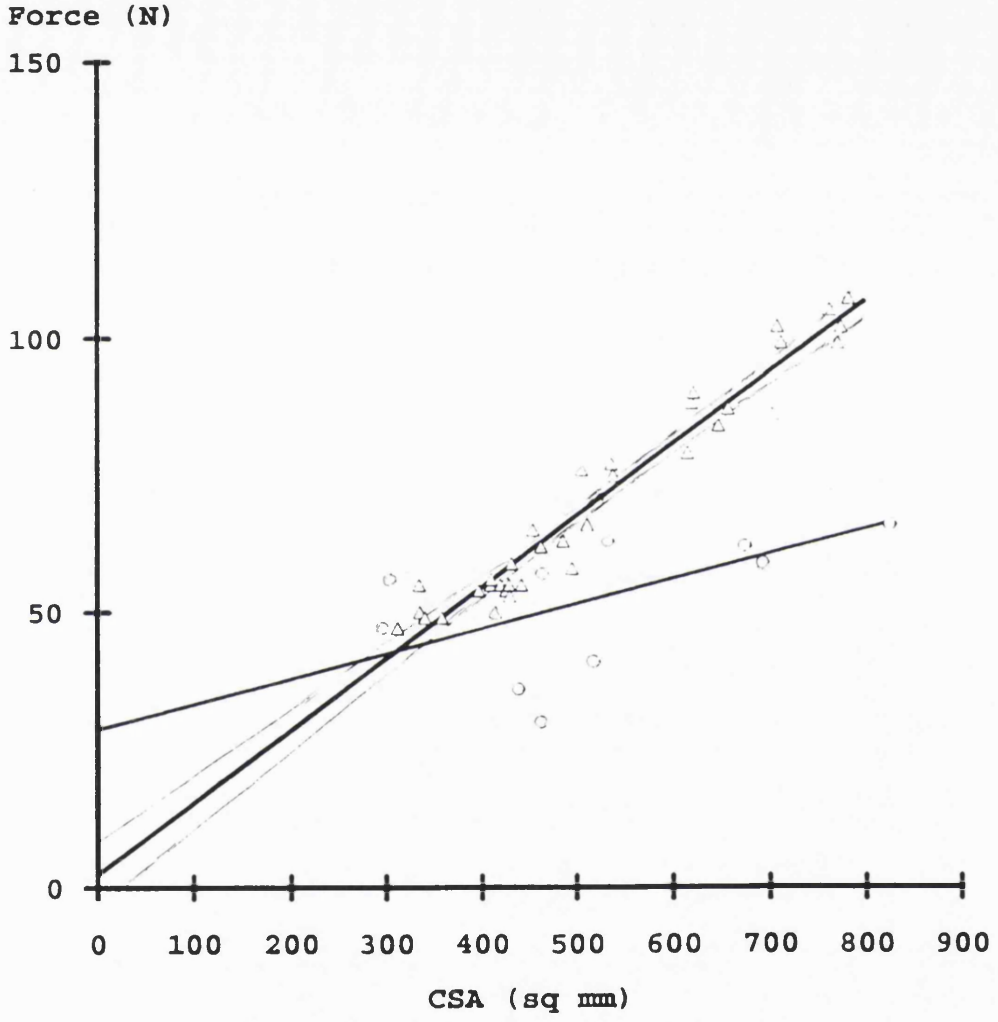
TABLE 14: MVF & CSA for 28 young controls (35 observations)

Name	Sex	Age	Force (N)	CSA (mm)	Force/CSA (N/mm^2)
AMH	F	23	47	312	0.15
LAG	F	25	55	334	0.16
RUF(L)			50	335	0.15
RUF (R)	F	25	49	340	0.14
GEK	F	23	49	358	0.14
GFC	M	40	54	397	0.14
KEE	F	23	55	409	0.13
CLF	F	24	56	410	0.14
LOA (L)			50	415	0.12
TEM	F	30	55	420	0.13
MAW	F	22	54	426	0.13
KAR	M	40	55	429	0.13
WID (L)			53	430	0.12
LOA (R)	F	24	59	432	0.14
ALC	F	28	55	442	0.12
YIC	M	31	65	454	0.14
FRB	M	32	62	463	0.13
UKN	F	22	63	486	0.13
WID (R)	M	33	58	495	0.12
JRB	F	28	76	505	0.15
DAN	M	31	66	511	0.13
KEN (L)			77	536	0.14
MIH	M	28	75	538	0.14
LXT	F	21	79	615	0.13
GLS (L)			88	619	0.14
GLS (R)	M	39	90	621	0.14
KEN (R)	M	24	84	647	0.13
VOC	M	24	87	657	0.13
EEL (R)	M	47	86	703	0.12
EEL (L)			102	708	0.14
TEW (R)	M	22	99	712	0.14
BJB	M	22	105	762	0.14
TEW (L)			99	771	0.13
MWH	M	19	102	774	0.13
THC	M	32	107	782	0.14
Number		28.00	35.00	35.00	35.00
Range		28.00	60.00	470.00	0.05
Mean		27.93	70.46	521.37	0.14
S.D.			19.35	143.99	0.01
CV			27%	28%	7%

Table 15: MVF & CSA for 11 elderly subjects

Name	Sex	Age	MVF	CSA (mm^2)	MVF/CSA	Stimulated?
MW	F	83	47	296	0.16	Y
RC	F	69	56	304	0.18	N
NC	F	82	36	439	0.08	Y
RU	M	83	30	463	0.06	N
WF	F	75	57	464	0.12	N
AM	F	85	41	517	0.08	N
BK	M	78	63	533	0.12	Y
WM	M	75	62	674	0.09	N
BW	M	83	59	693	0.09	Y
WI	M	82	72	770	0.09	N
PA	M	84	66	825	0.08	N
Number		11.00	11.00	11.00	11.00	
Range		16.00	42.00	529.00	0.12	
Mean		79.91	53.55	543.45	0.11	
S.D.			13.29	176.94	0.04	
CV			25%	33%	35%	

Fig. 18. MVF/CSA, 28 young controls and 11 elderly.



triangles = young controls

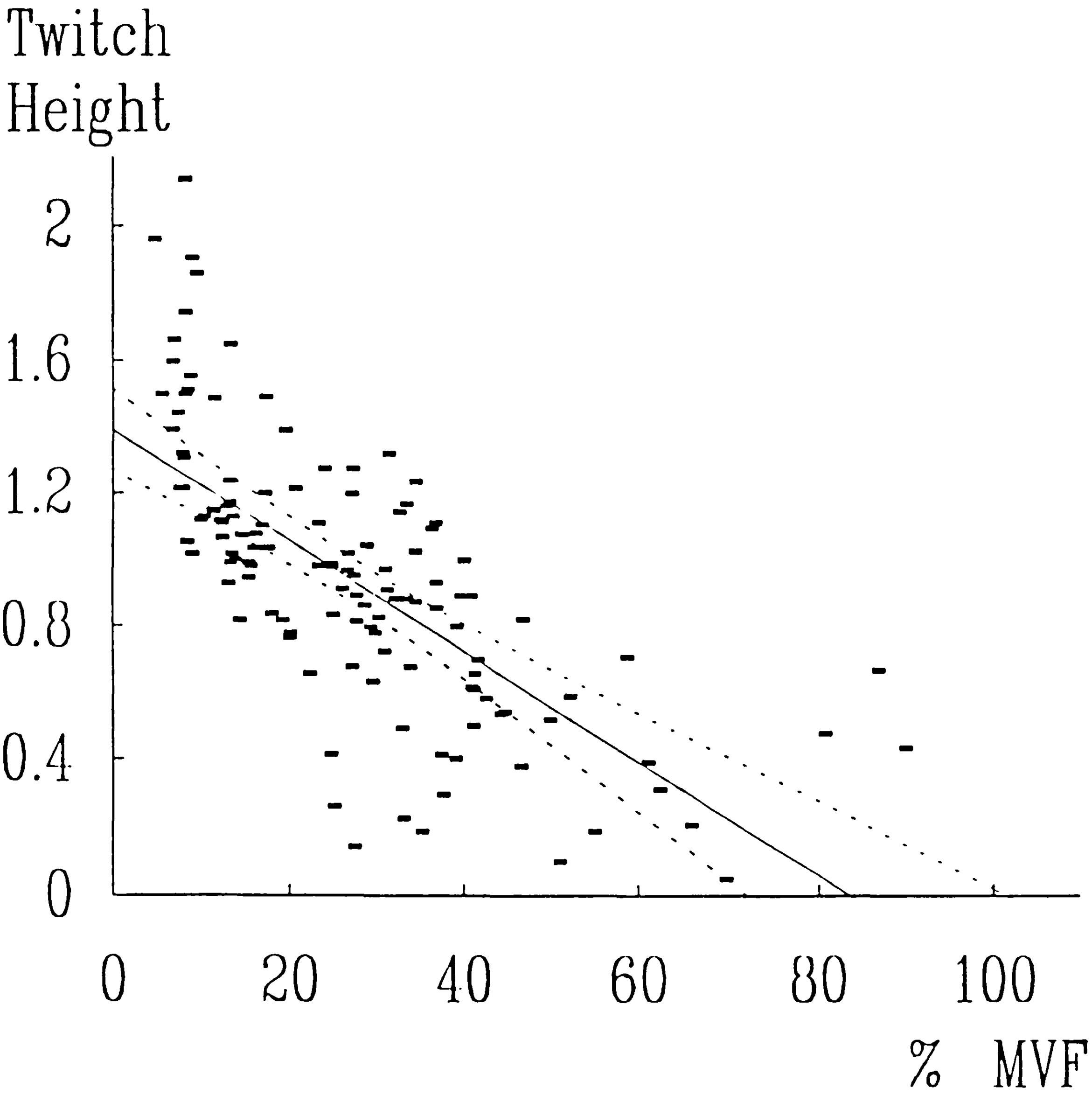
circles = elderly

thick solid line = regression line for young controls (r=0.95, P<0.001).

second thick solid line = regression line for elderly (r=0.61, P<0.05).

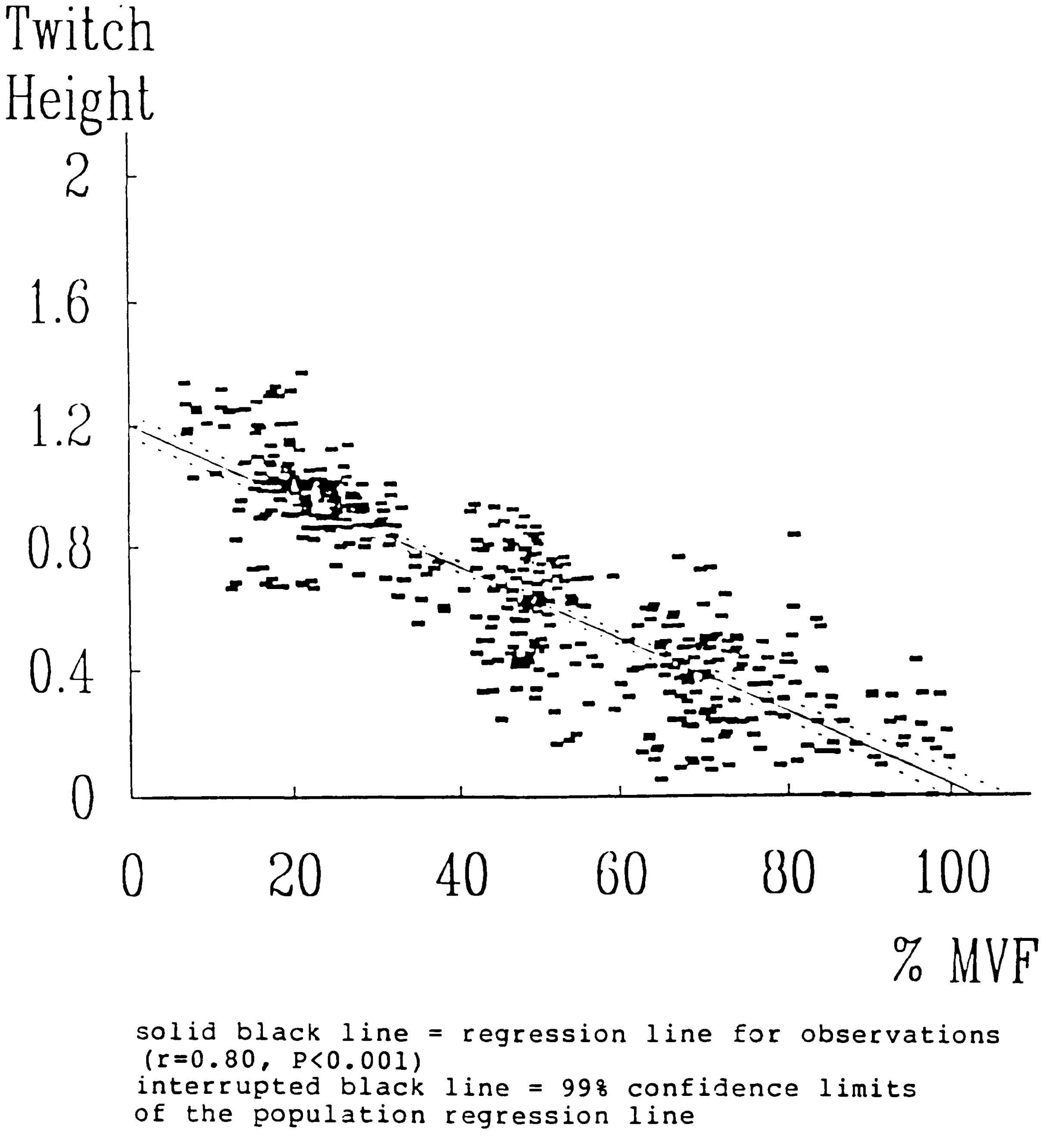
thin solid lines = 99% confidence limits for control observations

Fig. 19. Twitch height/%MVF, 3 elderly subjects.



solid black line = regression line for observations (r=0.66, P<0.001)
interrupted black line = 99% confidence limits of the population regression line

Fig. 20. Twitch height/MVF, 8 young subjects.



solid black line = regression line for observations (r=0.80, P<0.001)
interrupted black line = 99% confidence limits of the population regression line

muscle in young subjects (Rutherford et al, 1986a). Regression analysis is much easier for linear data. The data has therefore been transformed to a linear scale by plotting [normalised twitch height] against MVF. It can thus be seen that the regression line passes through zero at 100% MVF within the 99% confidence limits, indicating the likelihood of full muscle activation. It can be seen from Fig. 20 that there is apparent in most cases additional force recorded in response to electrical stimulation at the highest voluntary forces (to a lesser degree, this is also apparent in the elderly data, Fig. 19). This might be explained, in part at least, by inherent shortcomings of the apparatus used: a contributory factor to the scatter present in Fig. 20 (and Fig. 19) being equipment-produced 'noise'. The recorded noise is positive noise, contributing to the height of recorded twitches. The equipment is biased against 'negative noise' (ie: a negative twitch is not recordable by the apparatus).

The results for the three weak elderly subjects are shown in Fig 19. Data for one of the elderly subjects (MW) are not shown as her MVF/CSA was the same as for the young subjects. (Twitch imposition showed her to be able to fully activate her muscle.) The linearised results of the elderly are plotted in a similar way to those of the young controls. It can be seen that the regression line passes through zero at 100% MVF within the 99% confidence limits, giving an indication that full activation of adductor pollicis can be achieved by the weak elderly subjects.

DISCUSSION:

PART A: Effect of subnutrition on normalised muscle force and relaxation rate.

4.1 Weakness in the subnourished.

Muscle weakness in the subnourished is a common observation (Daniel et al., 1977). In addition, specific functional changes (most notably, slower rates of relaxation and increased fatiguability during voluntary contractions) have been reported in patients chronically subnourished secondary to gastrointestinal disorders (Lopes et al., 1982). The same changes have been reported in obese patients during diet or fasting (Russell et al., 1983a). It has been claimed that these observed muscle function changes were more sensitive indicators of nutritional status than standard clinical assessment techniques. A subsequent study (Brough et al., 1986) reported an improvement in muscle function upon refeeding (and consequent improved nutritional status) without change in muscle bulk as estimated by arm muscle area, suggesting that improvements in muscle function may precede recovery of muscle bulk. The inference that may be drawn from this is that there may be a difference in MVF/CSA relationship between normally - nourished and subnourished subjects.

The results show (c.f. 3.2) that the subnourished are weak relative to their height (used as an indicator of body build). They also have small muscles relative to their height. Their weakness is in proportion to loss of muscle bulk.

Two of the patients with Crohn's disease fall considerably outside the 95% confidence limits. One was on steroids, one an alcoholic. Steroids (Kendall-Taylor & Turnbull, 1983) and alcohol (Martin & Peters, 1985) are both known to cause myopathies which may have affected the results, although there was no specific clinical evidence of muscle disease in either of the two. In the ideal case, subjects on steroids and alcoholics, would be excluded from investigation, regardless of the lack of clinical evidence of specific muscle disease. However, the inclusion of the two subjects discussed above, and of another subject on steroids, was guided in large part by the difficulties of recruiting a sufficiently large group of suitable subjects.

The second of the two subjects had a coefficient of variation of force observations of 8.4%, compared to the coefficient of variation for the control group force observations of 2.2%, suggesting that contractions may not have been maximal. Even with these two individuals included, the subnourished group are not significantly different from the controls ($p=0.2$). This suggests that the most important effect of subnutrition on muscle is loss of bulk consequent upon its homeostatic function as a source of protein (Daniel et al., 1977).

4.2 Maximum relaxation rates

The difficulties involved in interpreting earlier studies of muscle function and nutritional status have been reviewed (Newham, 1986). Since then further studies (Lopes et al, 1982; Russell et al, 1983a; Russell et al, 1983b; Brough et al 1986; Chan et al, 1986) have reported slow relaxation rates in electrically stimulated adductor pollicis in subnourished surgical patients. Changes in force/frequency relationships have been observed and are explainable by prolongation of relaxation (Newham 1986).

The present finding that MRR is slower in voluntary contractions (as previously reported in stimulated contractions) in the subnourished, should make tests of muscle function in the subnourished easier and better tolerated, as the present apparatus is small, easily portable, and does not involve possibly uncomfortable stimulation.

The MRR of the control subjects was 25% slower than previously published stimulated relaxation rates (Newham 1986). This may be largely due to asynchronous activation of motor units during voluntary contraction. A numerical simulation of this asynchrony was carried out using a differentiated force record from one of the control subs. The record was averaged in a moving window of 80ms width. This depressed the peak value of fall of force by 27%, suggesting that this explanation is likely to be correct.

4.3 Summary

The present results suggest that measurement of maximum voluntary contractions would not be useful in diagnosis or follow - up of subnourished patients (using the present methods of measurement), as the major muscle function difference from normally - nourished subject's muscle is in muscle bulk, which is non-specific. (This finding is in contrast to the indirect inference from results of submaximal stimulated contractions [Russell et al., 1984] which suggest that subnutrition has a specific effect on the ability of muscle protein to develop force, perhaps though changes in calcium kinetics.) With a difference from the normally-nourished in force production but no difference in the MVF/CSA relationship, comparison between individuals, using the present equipment, would be difficult.

In conclusion, it would seem that voluntary MRR may be useful as an additional test in demonstrating marginal nutrition and assessing the efficacy of refeeding regimens in the subnourished.

DISCUSSION

PART B: Comparison of muscle cross-sectional areas obtained from CAT and n.m.r. images, with those obtained using the potentiometer rig.

4.4 Validity of CSA estimates.

The cross-sectional area measurements obtained using CAT and n.m.r. scans are absolute measures of muscle cross-sectional area: the muscle is delineated clearly on the scans and can be measured directly. The potentiometer measurements are estimations: skin and subdermal connective tissue and fat are included in the measurements, and some parts of the muscle are excluded due to the arbitrary limits of measurements). Plainly, CAT and n.m.r. scans provide a better measure of muscle CSA per se than do potentiometer estimations, and CAT scans in particular have been widely used for measurement of muscle CSA. However, what is required of the potentiometer rig is that it provide a reliable, reproducible, portable and inexpensive method of comparing the relationship between adductor pollicis force and cross-sectional area between individuals; absolute values of MVF/CSA ratios are not required.

Estimates of CSA obtained with the potentiometer rig are reliable; measurements correlate well with CAT and n.m.r. measurements (r=0.937). They are reproducible (mean coefficient of variation in CSA estimations in any one individual in the control group reported in 3.1 was 3.6%).

4.5 Methods of measuring/estimating muscle bulk.

Other investigators have used other methods to measure and estimate muscle size, principally: Ultrasonographic measurements of muscle CSA (Ikai & Fukunaga, 1970 [elbow flexors]), (Young et al., 1981 [quadriceps]), (Young et al., 1984 [quadriceps]); anthropometric estimations of muscle CSA (White & Davies, 1984 [triceps surae]); and anthropometric estimations of muscle bulk (Sargeant et al., 1976 [leg volume]).

As experimental tools, CAT and n.m.r, ultrasonography and anthropometry have considerable disadvantages.

CAT scans impart X-ray doses. This severely limits their use as a repeated measure. Also, CAT scanning is contraindicated in pregnancy; the risk of inadvertantly subjecting a volunteer in early pregnancy to a clinically unnecessary X-ray dose effectively limits CAT scan use to males and post-menopausal women. Measurements of muscle cross-sectional areas from CAT scan images (by the methods used in the present study) are time-consuming and the scanners themselves are expensive, relatively uncommon and hardly portable.

N.m.r., whilst being radiologically risk-free, shares other disadvantages with CAT. The measurement of CSA from n.m.r. images is equally time-consuming as with CAT. The machines themselves are even more expensive, uncommon and are completely non-portable.

The main disadvantage of other anthropometric estimations of muscle CSA or bulk is the grossness of the measure: allowance must be made for bone and skinfold thickness, and the variation in these factors between individuals is considerable. The approximate nature of anthropometric estimations are reflected in the relative poorness of correlations between muscle strength and muscle CSA obtained by this method (e.g: White & Davies, 1984).

Ultrasonography equipment is relatively expensive. Clinical ultrasound equipment can be portable, though not as portable as the potentiometer rig. The potentiometry rig is also considerably cheaper than ultrasonography and appears to meet very well the demands of the present series of studies for a hand-portable, cheap and reliable machine which may be used at the bedside.

4.6 Suggestions for future work

When the present study was carried out, it was planned to modify the potentiometer rig so as to enable direct and instant readings of muscle cross-sectional area estimates to be made. This modification could be made cheaply, using existing off-the-shelf equipment. It would involve the electronic integration of voltage outputs from two potentiometers. If made, it would obviate the need for an oscilloscope as a storage and display medium for the potentiometer rig's output, and would consequently render the CSA measuring equipment simpler more easily portable and cheaper to produce.

DISCUSSION:

PART C: Muscle parameter changes in the elderly.

4.7 Decreased specific force

The results show a decrease (27%±4% SEM; c.f. 3.5) in specific force in the muscle in the elderly group.

Other workers have also detected specific force decreases in the muscles of the elderly; Young et al detected specific force changes in the quadriceps muscles of elderly men (Young et al, 1985) but not in the muscles of elderly women (Young et al, 1984). Why might this be so?

(i) It may be that in muscles other than adductor pollicis, atrophy makes a greater contribution to strength decrease with age, and so specific changes could be more difficult to detect. In support of this is the fact that the correlations between force and cross-sectional area found in quadriceps by Young et al. were not as strong as were found for adductor pollicis in the present study.

(ii) The quadriceps group is a multipennate group and the relation between force and CSA is thus more complex than in a more parallel-fibred muscle such as adductor pollicis. This is because in a muscle group such as the quadriceps the muscle fibres do not lie parallel between tendons but insert into the tendon at acute angles.

This angle of pennation affects the force measured between the ends of the muscle. This is because as the angle of pennation increases more contractile tissue can be attached in parallel between the two tendons.

Individual variation in muscle architecture may account for some variability in muscle force generation; for example, resistance training could also alter the angle of pennation, changing the amount of contractile tissue in parallel, resulting in greater force production for a given CSA (Jones et al., 1989).

What might be the causes of a decrease in specific force with ageing? The following mechanisms may be implicated:

(i) A reduced activation ability.

(ii) An overestimation of contractile tissue CSA.

(iii) A preferential time-linked loss of type 2 fibres from the muscle (though this would be an unlikely explanation, as AP is composed predominantly of type 1 fibres).

(iv) Replacement of muscle by non-contractile material.

(v) Changes in connective tissue attachments within the muscle which may affect force transmission.

(Changes in fibre angles of pennation, affecting lever ratios are not a valid explanation of specific force loss in adductor pollicis with ageing (c.f. 1.5)

(vi) Chemical changes within the muscle fibre.

The above factors are addressed further in section 4.19, where they are discussed in relation to another group of elderly and the present group.

4.8 Atrophy

The ratio of force to height in the elderly shows a larger deficit as compared with the young controls (37±7% SEM) than does the ratio of force to CSA (c.f. 3.5). This is in accordance with previous studies (Grimby and Saltin, 1983). This indicates that the elderly muscles are not only relatively deficient in specific force, they are also atrophied. Implicated in this atrophy might be a time-dependant:

(i) Loss of motor units (Grimby and Saltin, 1983).
(ii) Decrease in fibre size (Essen-Gustavsson and Borges, 1986).

DISCUSSION:

PART D: Strength training of adductor pollicis.

4.9 Specific Force

The specific forces measured in the training group were higher than those of the young controls.
One possible reason for this is that the young controls were not fully activating their muscles.

It has been claimed that, prior to training, muscle cannot be maximally activated voluntarily, and that in the first month or so of training, activation increases as a result of increased neural drive. Evidence to support this view has come from surface EMG recordings. These recordings (though difficult to interpret) demonstrated an increase in 10% in the maximum integrated EMG as a result of training (Moritani & de Vries, 1978; Komi, 1986). Others report either no change or a decrease in maximum activation with training (Komi & Buskirk, 1972). This neural adaptation resulting in an increase in maximum voluntary strength could occur in two ways:

1. Training may in some way bring about the recruitment of large and fast motor units. These units are only recruited at high forces. In maximal voluntary activation of the muscle not all muscle fibres are activated together; typically, type 1 fibres are

activated first, followed by activation of type 2 fibres as the force of the contraction rises. The argument is that in untrained individuals there are some units which are not recruited in a maximal voluntary contraction.

One way of finding out whether a maximal voluntary contraction is fully activating a muscle is to stimulate the contracting muscle and see if any additional force can be obtained (Merton, 1954 [adductor pollicis]; Gandevia & McKenzie, 1985 [diaphragm]; Rutherford et al., 1986 [quadriceps]; Chapman et al., 1984 [quadriceps]). It appears that, at least in the muscle groups cited in these studies, untrained individuals can maximally activate their muscles. The stimulation study which comprises part of the present series of studies (c.f. 4.16) demonstrates that untrained individuals, young and elderly, can fully activate their adductor pollici. It seems therefore that an increased activation of this muscle is an unlikely explanation for the observed high specific forces in the present study.

2. There may come about with training a change in the pattern of stimulation of the motor units, producing greater measured forces during MVC's. The work of Rack and Westbury (1969) and Petrofsky and Lind (1978) is reported in a review of muscle changes in strength training (Jones et al., 1989) as demonstrating that

asynchronous stimulation (at a relatively low frequency) of a divided nerve generated more tension than synchronous stimulation at the same frequency. The argument is that with synchronous stimulation all motor units will be activated together and as tension develops they will stretch the series elastic elements; the muscle will be shortening and will consequently develop less than the maximal isometric force. With asynchronous stimulation, the series elastic elements will be stretched by the first part of the muscle to contract and remain stretched as the subsequent portions contract isometrically and generate full force. This effect could affect peak forces in unfused tetanic contractions or the rate of rise of force in fused tetanic contractions, but would not be expected to affect peak force in fused tetanic contractions, since in a fused tetanic contraction at plateau, the muscle does not undergo further shortening, and all elastic elements available to be stretched have been stretched. In fact, the balance of evidence for changes in pattern of stimulation in trained muscle as summarised by Komi (1986) is for an increase in synchronisation, not a decrease. This would be expected to lead to a decrease in measured MVC, not an increase. To summarise, then, it seems unlikely that neural adaptation, whether by changes in stimulation patterns or by increase in recruitment in the training group in the present study could be a likely mechanism for the high specific forces measured.

4.10 Skill acquisition

Another possible explanation is that in the period allowed to the trainers prior to the training period, a time in which they were encouraged to familiarise themselves with the testing apparatus, a skills aquisition effect occurred; the trainers became skilled at the use of the apparatus. As mentioned in 3.8, the skills acquisition curve must have plateaued early, since there is no significant increase in specific force subsequent to the baseline tests. Rutherford and Jones (1986) have demonstrated this effect in a study which involved subjects lifting near-maximal weights on a leg extension machine over a 12 week period. After training, the improvement in training loads was 200%, but the increase in isometric strength was only 15%, and power output (measured in an unfamiliar fashion to the subjects), did not change. Rutherford and Jones conclude that such a lack of cross-over of performance suggests that the large increase in training weights lifted was largely attributable to skill acquisition in the weight-lifting task.

Both the training and measuring tasks in the present study involved very similar equipment. It is known that the force-measuring apparatus lent itself to contributions from the long flexors of the fingers. This muscle group is large, therefore small variations among individuals in the degree of skill acquisition (and/or intrinsic strength) in the use of these muscles as a result of training and measuring activities might be expected to be reflected in large variation among individuals in percentage strength change between pre- and post-training measurements. In fact, the range of individual post-training force changes is high (48). Conversely, the range for this factor in the untrained hand is half of that in the trained hand (24), possibly reflecting the fact that the accessory muscles of the untrained hand were trained only during measuring contractions but did not receive the potentially strength-/skill-acquiring benefits of training contractions. This reinforces the conclusion that the increase in specific force in the trained adductor pollici came about as a result of skill acquisition in the use of muscles accessory to the action of adductor pollicis, primarily the long flexors of the wrist, the contribution of which the force - measuring apparatus was sensitive to, and which was duly included in the MVC measurements.

4.11 Strength increase.

Another question to answer is, why did training produce no detectable increase in strength?

Heavy resistance training makes muscles stronger (Costill et al., 1979; Delorme [quadriceps], 1945; Thorstensson et al. [quadriceps], 1976; Duchateau and Hainault [adductor pollicis], 1984). The closer the similarity of training activity and measuring activity (ie - the more specific the training) the better; the same applies for the length of time that the muscle is fully activated (Rutherford and Jones, 1986).

It would seem reasonable to expect that a training study which bore the above factors in mind (ie-was specific enough in its training and measuring and included enough time for a training effect to become apparent) would bear fruit in terms of an increase in strength of the trained muscle. The present study was specific in terms of training activity, which was made as similar as possible to the strength measuring activity. In retrospect, however, it is apparent that the training time was not long enough to bring about detectable change; it is likely that any strength change with training would have been masked by the inherent variability of the force-measuring equipment and technique.

Duchateau and Hainault (1984) carried out a training study on adductor pollici over 90 days, comprising 10 maximal contractions/day, each of 5 seconds duration. This adds up to 4500 secs of training. After training they measured a mean 19.7% increase in isometric strength.

The present training study comprised 30 two - second contractions/day for 25 days, 1500 seconds in total, a third of the total activation - in - training time of Duchateau and Hainault. It might be reasonable to expect, then, that since specificity of training and degree of activation are similar in both studies, a training activation time of one third of the Duchateau study would result in an increase of isometric strength roughly one-third as large. One might expect at the completion of the present study a strength increase of roughly one-third of the Duchateau training - induced strength increase (ie; 6.6% or thereabouts).

Unfortunately, a strength increase of 6.6% is not detectable using the force - measuring apparatus of the present study. The coefficient of variation of the MVC measurements (trained and untrained hands) at each time of testing ranged from 2.4 - 20.7%, mean 8.37%. Given this coefficient of variation in strength measurements, a measured strength increase of 6.6% upon training would not achieve significance.

(The coefficient of variation of the MVF measurements in the training group [mean, 8.37%] are considerably higher than in earlier reported studies [COV for young controls' MVF's {c.f. 3.1} was 2.2%] this possibly reflects an increased variation in size of contribution of accessory muscle in measured MVFs in the training group, as a result of a learning effect).

It might be argued that,if the present study had been of three months duration, training effect in terms of a strength increase pre/post training might have become detectable (expected strength increase = 3x6.6%, = 19.8%). 19.8% increase would have been detectable using the present apparatus, being more than 2x the coefficient of variation of the force-measuring apparatus.

4.12 Bearing of results on future training studies

It had been suspected before the training study was carried out that the force testing apparatus lent itself to contribution of accessory muscles, mainly the long flexors of the fingers, in the measurement of adductor pollicis strength. In the present study, a learning effect seems likely to have occured in the use of accesory muscles in the period of force-measuring apparatus familiarisation prior to training, resulting in high MVFs, apparently due to an increase in accessory muscle involvement in MVFs. The time allowed to subjects for force-measuring apparatus familiarisation in the previous reported studies, however, was minimal, reflecting, it is assumed, a much smaller contribution from accesory muscles in measured MVFs.

The evidence of contribution of accesory muscles to measured MVFs prompted the development of a new force-testing apparatus less predisposed to accessory involvement.

The main purpose of this pilot study was to ascertain the suitability of the MVC training equipment and regime, with a view to using the same, modified in the light of experience, in a longer-term, future study. It was not expected (though it may have been hoped) that a training programme of the pilot study's length would result in clear-cut results in terms of significant changes in force and/or CSA. If a small training effect occurred over the course of the present study, it was obscured by variability in force and area testing.

Despite the lack of clear-cut training effects valuable lessons have been learned.

These include:

1. The desirability of modification of the force-testing apparatus to reduce or eliminate the involvement of the long flexors of the fingers in force testing (see above).

2. The neccessity, in any future training study (even using improved, less learning-effect prone equipment), of repeating baseline measurements in order to eliminate the risk of initiating testing and training on the upward slope of a training curve.

3. The neccessity, in any future training study, of either reducing the variability of force and area testing measurements (a consideration partly dealt with in the developing of the new force-measuring apparatus), or of extending the duration of the study, or both.

DISCUSSION

PART E: An investigation of adductor pollicis force and cross-sectional area in a group of experienced fencers

4.13 Bar-type force transducer.

One of the aims of the present study was to evaluate the performance of the bar-type force transducer, developed with the intention of eliminating the contribution of the long finger flexors in measurements of MVF.

It is evident that the forces obtained with the bar-type tranducer in the present study are considerably lower than those obtained in a comparable group of subjects (c.f 3.1) using the old-style transducer. It is likely that this reduction is due to the elimination of the long finger flexors.

One of the benefits of eliminating long flexor contribution in the present study has been a much better force/CSA correlation: the correlation (for fencers and stimulation control groups combined [c.f. 3.10]) is r=0.97, considerably better than that obtained for the young control group measured with the 'old-style' force transducer (r=0.88 [c.f. 3.1). Another benefit has been that the coefficient of variation of the MVF measurements in the fencing group (range 2.1 - 7.5%, mean 4.84%, n= 14) is lower than that of the 'old-style' control group (range 2.54 - 20.27%, mean 8.37%, n=36). This decrease in MVF CV was reflected in a subsequent group (c.f. 3.10).

4.14 Training effect

It was hoped that it would be possible to demonstrate a training effect in terms of change in force and/or CSA in the (presumed) trained fencer's adductor pollices. The shortness of the training study was probably a causative factor in its lack of clear-cut result; another probable main cause was the inadequacy of the oldstyle force transducer. In the light of the training study experience, the transducer was improved, with a view to using it in a longer version of the original training study.

4.15 Projected further training study

The fencers were thought to be good candidates for a pilot study of this projected study, since it was assumed that, their fencing-hand adductor pollices having been trained regularly for two years or more, any training effect in terms of force and/or CSA would, with the improved apparatus, be readily apparent. That no such effects were evident could have been for either of the two following reasons;

1. The intensity and frequency of adductor pollicis muscle training undergone during fencing practice was insufficient to produce a training effect.

2. A training effect did occur, but was too small to be detected by the present apparatus.

These possibilities are discussed further in 4.11, where the present results are compared with the results of a long-term adductor pollicis training study (Duchateau & Hainault, 1984).

DISCUSSION

PART F: Adductor pollicis activation in the elderly.

4.16 Activation

A possible contributory factor in the decreased specific force observed in the elderly in the present study and in the earlier reported study (3.1) is that not all the muscle is fully activated, either because of a lack of subject motivation or reflex inhibition, which are both known to cause muscle weakness (McComas et al., 1983; Rutherford et al., 1986). It is this factor that the present study attempts to address.

4.17 MVF/CSA variability in the young.

The MVF/CSA ratio measured in the elderly in the present study is 26% less than that of the young controls. This is in agreement with MVF/CSA ratios reported in the previous elderly study (3.5). It is notable that there is less scatter in the young control MVF/CSA observations in the present study than in the previous study. This is probably because (as discussed in 4.10) the method of force measurement used in the previous study lent itself to contributions from the long finger flexors. The force measuring apparatus used in the present study was designed to eliminate the possibility of contribution from the long finger flexors. It is likely that in the previous study the proportion of MVF attributable to the long flexors differed appreciably between individuals, depending on such factors as flexor muscle size and degree of activation, and that this varying contribution accounted in large part for the greater scatter in MVF/CSA observations in the earlier study.

4.18 MVF/CSA variability in the elderly.

Conversely, the elderly observations in the present study show more scatter than in the earlier study, with some of the MVF/CSA observations being no different from those of the young. (No correlation was found between age and MVF/CSA ratio in the elderly group, neither was there any difference in this ratio between males and females in this group.) It is possible that the elderly show greater variability in MVF/CSA ratio than did the corresponding elderly group in the previous study, because the elderly subjects in the present study are generally fitter than those of the previous group. Thus they may include some who are of a lower 'biological age' than their chronological age. The elderly were selected by questionnaire for their fitness in terms of outdoor independence. There is evidence for fitness being a measure of physiological reserve, and therefore of biological rather than chronological age (Lancet Editorial, 1991). Other studies (notably Young et al., 1984, 1985) have had difficulty demonstrating a difference in MVF/CSA between elderly and young subjects, possibly because of this variability.

4.19 Decreased specific force in the elderly

(The present finding of a reduced MVF/CSA ratio in the elderly tends to confirm the similar deficit found in the group of elderly [Day-centre and GP lists-recruited] group reported on in section 3.5.)

(i) Activation

It could be that the observed greater variability in the elderly is due to differing degrees of muscle activation between individuals and that only those individuals whose MVF/CSA ratio approached that of the young achieved full activation. However, the results indicate that this is probably not the case; even the elderly with low MVF/CSA ratios show evidence of fully activated muscles during MVF (c.f. 3.11). This is in agreement with Vandervoort and McComas (1986) who found by twitch interpolation (at MVF only) that most elderly subjects could fully activate their ankle muscles, though it is unclear whether these elderly subjects had a low MVF/CSA ratio.

(ii) Overestimation of contractile tissue CSA.

Another possible explanation for the observed force deficit in the elderly is that there has been an overestimation of contractile tissue CSA. However, muscle CSA's obtained by the present potentiometer method correlate well with CAT and nmr scans of muscle cross - sectional area taken in young subjects (c.f. 3.4). There is no evidence to suggest that the adductor pollicis of elderly subjects differs substantially in its connective tissue content, at least, not enough to account for a 26% deficit in MVF/CSA. Orlander et al., (1978) found no increase with age in lipid droplet content as a percentage of cell volume in vastus laterali of men. Also, the percentage of muscle volume taken up by connective tissue is not large; only about 1% of muscle volume in 3 month old rat muscle (Alnaqeeb et al., 1984).

There is evidence suggesting that the reduction in MVF/CSA with ageing is not due to a decrease in muscle contractile tissue content. Work on isolated young and elderly mouse muscle has demonstrated a decrease in isometric and shortening force with ageing, but no reduction in force during active stretch (Phillips et al., 1991). There is evidence that this may be true for human muscle (Vandervoort et al., 1990). If the reduction in MVF/CSA were due to a decrease in contractile tissue content of muscle, then stretch force would also be lower.

(iii) Type 2 fibres-stronger than type 1's?

It has been suggested that type 2 muscle fibres are inherently stronger than type 1 fibres (Young et al., 1984; Grindrod et al., 1987), and Type 2 fibre atrophy has been associated with ageing (Essen-Gustavsson & Borges, 1986; Lexell et al., 1988). Such an atrophy would contribute to decrease in MVF/CSA with ageing. However, adductor pollicis is composed 80 - 100% of type 1 fibres (Round et al., 1984). Selective atrophy or loss of type 2 fibres does not therefore seem to be a valid explanation for MVF/CSA decrease with ageing in the present study.

(iv) Chemical changes.

Another possible explanation for MVF/CSA decrease with ageing is that there occurs with ageing a chemical change in the muscle which affects the ability of the muscle to exert force. A raised intracellular phosphate concentration or lower intracellular ph are known to cause muscle weakness in isolated young animal muscle (Curtin, 1991). One in vivo study of human muscle showed no difference in muscle metabolites with ageing (Taylor et al., 1984). However, variation between subjects was large, and may have masked differences between young and elderly which though small, may have been sufficient to reduce force.

One possible explanation is that the actin-myosin cross-bridge connection in a contracted muscle has two possible states: high energy and low energy. There is the possibility that there is an age-linked progressive loss of ability to effect the high energy state.

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