In The Name of God

AN INVESTIGATION OF THE BIOMECHANICS OF KNEE EXTENSION IN TRAINED AND UNTRAINED SUBJECTS.

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AUTHOR'S DECLARATION

I declare that this thesis embodies the results of my own special work, that it has been composed by myself and that it does not include work forming part of a thesis presented successfully for a degree in this or another University.

Signed: ....

Date: 5/10/2001

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I am grateful to my friends, and classmates and fellow students, who supported and encouraged me throughout this project.

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Dedication

This thesis is dedicated to my father who left this life before he was able to share in my success and that of my family.

ABSTRACT

Contemporary sportsmen and sportswomen require high standards of performance and the promise of continuous developments. The study and application of biomechanics to sport offers one way of improving performance.

It is particularly important to understand the mechanical properties of skeletal muscle and how training might change these. The most fundamental studies of these properties have used laboratory animals and subsequent work has extended the understanding of human muscle. The results reported in this thesis came from experiments, which investigated the maximal knee extension torque and the maximum knee extension velocity in a group of normal young humans.

The scientific literature contains many reports of training studies. These use a wide range of protocols and most report the maximum forces produced before and after training. Rather few reports of changes in maximum velocity can be found. The aim of the experiments was to investigate both force and velocity changes since they both contribute to muscle power.

Two series of experiments were performed. The first was a training study to which 25 young adult subjects were recruited. Seven subjects were withdrew and 18 (10 females, 8 males) completed a six week training programme. Measurements of isometric torque and isokinetic torque during knee joint extension were performed at intervals of two weeks. The training

produced statistically significant increases in mean isometric torque at all angles tested.

At 70° of flexion the initial and final mean values were 814.9 ± 223.8 Nm and 987 ± 255.7 Nm. The isokinetic torque also increased at 60°/sec. The initial and final mean torques were 617.8 ±148.7 Nm and 724.2 ± 190.2 Nm.. Similarly, at 180°/sec the initial and final values were 525.2 ± 149.8 Nm, and 642.9 ± 89.8 Nm. In a separate series of experiments on the same volunteers, the maximum velocity of knee extension also increased over the training period. The initial mean value was 219.6 ± 49.3 deg/sec and the final mean value was 297 ± 84 deg/sec. These changes were statistically significant at the level of $p > 0.05$.

The aim of the second series of experiments was to investigate the length-tension and force-velocity characteristics of 25 untrained volunteers. The mean maximum torque was 971± 237 Nm, observed at 80° of knee flexion. It fell to 745 ± 187 Nm at 110°, to 645 ± 171 Nm at 50° and to 209 ± 71 Nm, at 10°of flexion. The velocity of knee extension was recorded under a series of loads up to the maximum the volunteer could lift. There was a wide range of maximum velocities recorded (169-379 deg/sec). The velocity slowed as the load increased but all volunteers stopped abruptly rather than gradually slowing under very heavy loads.

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INTRODUCTION

Training processes are important in sport as athletes work to improve their performances. Year by year improved performances in a whole range of sports are seen. Coaches and sports scientists are both involved in the training process but often they work in different directions and have different experiences and opinions. Coaches suggest personal opinions to solve any technical problems. These opinions are often based on trial and error. They may have to address specific errors in technique in an individual. In addition, coaches determine training periods, which are convenient for competition with the aim of improving results for an individual rather than finding more specific approaches for athletes in general. On the other hand, scientists treat sporting performance as a science. Scientists design experiments to identify important characteristics of the volunteers for their experiments. They determine training periods for experiment in terms of sessions per week, repetitions and sets. Sports scientists most often test performance using laboratory-based equipment. They analyse the results to search for statistical significance rather than comparing results in competition. In conclusion, coaches and sports scientists should work together to improve the quality of technique and performance of athletes.

Much of what is known about muscle mechanics comes from experiments using isolated muscles from animals such as frog, mouse, rat or rabbit. These experiments use external electrical stimulation to investigate muscle properties such as the length tension and force velocity relationships.

This ensures complete activation of the muscle. When experiments are done with human volunteers, the muscles are usually activated by voluntary effort and so it is not possible to be certain of the extent of activation. In whole human limbs the position is even more complicated.

Many muscles are activated together to produce voluntary movements. For example, quadriceps has four parts, each of different length with different fibre architecture, some arranged in parallel and some pennate, and with different mechanical actions. Rectus femoris acts to extend the knee and flex the hip. The other three heads of quadriceps only extend the knee (Tortora, 1999). The ultimate mechanical action at the knee might also be determined by the activity of antagonist muscles such as hamstrings. If it is active, hamstrings can increase the knee extension torque delivered by rectus femoris by opposing its action as a hip flexor. It can simultaneously reduce the knee extension torque of the other heads of quadriceps. However, even with all these complications, the essential muscle characteristics of the length tension and force velocity relationships can still be observed in human limbs.

The length tension relationship for human muscles is usually investigated by a series of isometric contractions at a range of joint angles rather than a range of muscle lengths (Lindh, 1979). The force velocity relationship is usually investigated using isokinetic techniques where the torque produced at a fixed velocity of joint rotation is measured rather than linear shortening velocity under constant load (Kellis & Baltzopoulos, 1997). In both of these types of experiment it is difficult to measure muscle fibre length since individual fibres are shorter than whole muscles and they may lie at oblique angles (Alexander & Vernon, 1975).

However, maximum force is generated at one specific joint angle, as expected from the length-tension curve. In addition, torque changes with the velocity of joint rotation. Peak torque occurs at low velocities and falls progressively as velocity increases. This relationship is the basis of the well-known force / velocity curve (Jones & Round, 1990).

Length tension relationships

The length of a muscle affects the maximum force produced. This is shown in figure 1. The force is greatest near the mid-range of the muscle fibre length. At shorter and longer lengths the force is reduced. The optimum length is known as L_0. This ultimately reflects the extent to which actin and myosin filaments overlap. At L_0 the maximum number of cross bridges form and so maximum force is developed. In whole limbs the range of muscle lengths is restricted by the skeletal attachments to approximately $\pm$ 20% of the resting length and so the force never falls to zero. The full-length tension relationship is observed only in isolated muscles where the length change is not limited by attachment to bones. In addition, there are species variations and some frog and toad muscles can be extended to lengths far beyond that of human muscle since their thin filaments are slightly longer (Gordon, Huxley & Julian. 1966).

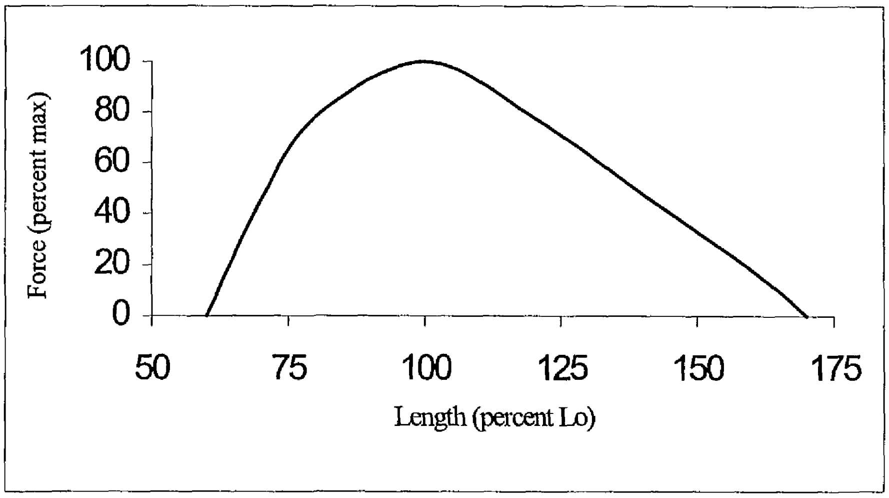


Figure 1. A typical length tension relationship for skeletal muscle showing lengths and forces as percentages of their maxima.

Force velocity relationships

In both isolated muscles and whole human limbs, the external load significantly affects the velocity of shortening of muscle. The greatest velocity of shortening occurs when the external load is zero. The range of velocity for type I fibres can be as high as 2 fibre lengths/second. Type II fibres can reach 6 fibre lengths/second. However, whole muscles can reach velocities of 4 muscle length/second (Wilkie, 1950). As loads increase the velocity of shortening falls and ultimately it becomes zero when isometric conditions occur.

Effect of fibre type

Human muscles have two principal types of fibre: slow twitch and fast twitch. Type I slow twitch fibres have oxidative metabolic pathways and have a slower range of shortening velocities. During twitches they take about 110 milliseconds to reach peak tension. The more glycolytic type II fibres can reach peak tension in 50 milliseconds during twitches. The maximum speed of shortening of human muscles may well be affected by the ratio of type I/II fibres. The more type I fibres, the slower the muscle should be (Billeter & Hoppeler, 1992). Type I fibres have greater endurance and when combined with good cardiorespiratory function, they can give an athlete the capacity to sustain exercise. This is found in long distance cyclists, runners or swimmers. On the other contrary, type II fibres have poorer endurance. These fibres can deliver high forces for short periods. They are used in athletic competitions such as the throwing events in field competitions, weightlifting or sprinting. The high forces they generate can stop blood flow. The pressure developed inside the muscle compresses, and possibly closes the blood vessels. (Bull, Davies, Lind & White (1989), Wright, McCloskey, Fitzpatrick (2000). Thus depending on the extent of circulatory obstruction, the muscle fibres fatigue more or less rapidly and recover when blood is delivered to the muscle after the contraction stops.

Attempts have been made to investigate the influence of fibre properties on whole limb performance by biopsy studies (Harridge, Bottinelli, Canepari, Pellegrino, Reggiani, Esbjornsson, Balsom & Saltin, 1998). The difficulty with all of the biopsy studies is that only a small part of one or two muscles is sampled. Biopsy samples are usually 50-100 milligrams of tissue from a muscle which may weigh several kilograms. These samples may not give a true picture of conditions in the whole muscle. No information is obtained about the fibre orientation. In training studies, where before and after biopsies are taken, it is hard to be sure that similar regions of the muscle were studied. In addition, these studies provide no information about neural adaptations during the training process.

Human measurements using Kin Com

Many recent studies of human muscle performance use isokinetic machines of the Kin Com type to investigate muscle function. These machines measure joint torque at a constant angular velocity of joint rotation i.e. under isokinetic conditions. Many muscles under voluntary control generate the torque. These muscles need not share a common Lo or maximum shortening velocities. There is even the possibility of antagonist muscle activity (Kellis, & Baltzopoulos, 1999). Consequently, isokinetic experiments give little direct information about muscle mechanics but they do allow investigation of limb function under reasonably normal conditions.

Torque causes movement in a circle. Torque is the product of force and distance. Force is generated by muscle contraction and in experiments, the distance is measured as that between the centre of the strain gauge and the axis of rotation of the joint. With practice by the experimenter and the experimental volunteer, the Kin Com allows consistent measurements to be made. Test re-test reliability scores can be as high as 0.98 at moderate velocities of 180 degrees/sec though these values can fall to 0.87 at 300 degrees/second (Caiozzo, Perrine & Edgerton, 1981)

Factors affecting force and velocity

Many factors affect the maximum force and maximum velocity of shortening muscles. These include temperature, fatigue, nutritional status, pain and hormonal status. Experiments using isolated muscle allow many of these factors to be controlled by the experimenters. In training studies with humans it is difficult to keep these factors constant or even to measure them. This is a significant problem in all training studies.

Muscle properties and training

Muscle properties are determined partly by genetics and partly by the pattern of muscle activity (Bounchard, 1990). There is continuing discussion about the relative strengths of these two factors. However, it is well known that muscle properties can be changed by appropriate training routines. Training can improve the capacity of muscle to sustain its mechanical performance or to increase the peak power.

The training routines for these two requirements are quite different. Increased endurance is a result of high repetitions of low intensity contractions (McArdle, Katch and Katch, 1994). Increased strength or power is a result of low number of repetitions of high intensity contractions (McArdle et al 1994). It is difficult to combine both of these requirements in one training plan. The experiments described in this thesis investigate the effects of strength training on leg biomechanics and so this description will concentrate on strength training.

Many changes are associated with strength training. These include changes in the size of the muscle fibres and changes in the percentage composition of fast and slow fibres (Hakkinen, Alen & Komi, 1985). In addition, there are changes in the neural activation of motor units (Sale, McComas, McDougall & Upton, 1982). These might include the numbers of active motor units, the firing frequency of individual motor units and the reflex connections to motor neurones. However, this would also include the timing of muscle activation and the co-ordination of muscle actions. These features need not all change to the same extent or at the same time. Early in the training period, the main effects are neural. This is clearly shown in an investigation of strength training done by Sale, et al (1982). They studied changes in the force and integrated electromyogram of thenar muscles during a five-week training period which gave a mean increase of 40% in voluntary strength. Analysis of motor unit firing showed that all motor units in the muscles were active during maximal contractions before and after training. However the integrated electromyogram was significantly greater after training. This strongly suggests that motor unit firing frequency had increased. Thus training for short periods accessed a reserve of neuromuscular function. The training did not affect the reflex properties of these muscles. However, de-training the muscle had significant effects on reflexes. The muscles had faster twitch characteristics after training, through this was a smaller effect, 8% on average, compared to the force increase. With longer periods of training it is possible to detect progressive hypertrophy of muscle fibres. In 1985, Hakkinen, Alen and Komi described a 21-week strength-training programme carried out by eleven volunteers already accustomed to strength training. They found an increase of 26.8% in knee extensor strength. This was significantly correlated with increasing integrated electromyogram. These again suggest an increased use of a neuromuscular reserve, even in volunteers who train regularly. This study did not investigate the behaviour of individual motor units in large muscles. They did find that integrated electromyogram rose higher earlier in the maximal contractions. This accompanied changes in the force time curve. This must reflect earlier, stronger activation of the muscle. Perhaps this is important in tasks requiring quick high force movements.

However, this study did take muscle biopsy samples. They found a selective hypertrophy of fast twitch fibres. The increases in muscle fibre cross section area were highly significant over the first 12 weeks of training there was no significant hypertrophy in the second half of the training period. The volume of exercise generally controls the adaptation of muscles to training.

After six weeks of training, muscle fibres show signs of hypertrophy and possibly hyperplasia (Hakkinen et al, 1985). Hypertrophy is responsible for the increases in muscle mass with longer training periods. Hypertrophy occurs in all fibre types, though some studies indicate hypertrophy is greater in type II fibres than in type I fibres (MacDougall, Sale, Moroz, Elder, Sutton & Howald, 1979 ; Staron, Malicky, Leonardi, Falkel, Hagerman & Dudley, 1990).

Hyperplasia is an increase in the number of muscle fibres. There is good evidence of hyperplasia in animal experiments but the evidence of hyperplasia in human studies is weak (McCall, Byrnes, Dickinson, Pattany &

Fleck. 1996; Gonyea, 1980). The evidence for hyperplasia in humans may be difficult to obtain because it is very difficult to determinate muscle fibre numbers (Larsson & Tesch, 1986). Heavy resistance training may cause an increase in size of muscle fibres per motor unit (McCall et al. 1996). Some experienced athletes may possess larger motor units than untrained individuals but this still largely speculation.

The training programme for an athlete is generally planned in terms of a whole year. Specific observations of the athlete's performance many cause changes to be made in the training programme. It is necessary to relate the training programme and the performance. Probably every individual has different responses to the similar training stress. In is well known that untrained volunteers show much larger responses than those who increase an established training pattern.

A major difficulty in understanding strength training comes from the different programmes in use in different countries. This was made worse by great secrecy of training methods in the former Communist states, though their record of success in competition was very impressive. However, whilst the role of illegal drugs in their training programmes remains unresolved, many Western authorities are certain drugs played a part in their success. More information about "Russian" training is now available. It requires very high loads and volumes of training. It appears designed for athletes already at a high standard rather than for those in development. The high loads risk serious injury to those who use them. However, other countries such as those in Western Europe, tend to use lighter loads in training.

force development (Jones & Round, 1990). In addition, training changes the speed with which muscle cells release calcium ions.

Human motor units fire at rates between 10 and 30 Hz during most voluntary contractions (Basmajian & DeLuca 1985). This reflects the balance of central nervous system influences and motoneurone properties. There is evidence of strength training increasing the motor unit firing frequency (Sale 1988)

In conclusion, much is known about the molecular mechanisms of force development in isolated muscle fibres. A considerable amount is known about muscle usage and the genetic expression of fibre types in animal muscle. However, rather less is known about the changes in the performance of humans during conventional training.

Aims of the project

In this project it is proposed to define the characteristics of knee extension movements in normal, young adults and then to investigate if these are altered by a brief period of training. The project aims are listed below.

1. To establish the isometric torque and torque under isokinetic conditions of the knee extensor muscles in an untrained population.
2. To investigate knee extension velocities under a range of loading conditions.
3. To investigate the changes in knee extensor torque and knee extension velocity as a result of training.

METHODS

This thesis describes two series of experiments. One was a training study. The other was an acute study, which examined the force and velocity of knee extension in volunteers on a leg press machine. Each set of methods will be described separately.

The training study

The participants in this study were students in the University of Glasgow. The volunteers were recruited by an invitation placed on the class web site. In total, twenty-five volunteers, fifteen females and ten males, who fitted the entry criteria were recruited for the study. They were healthy and no history of disease. The volunteers' height was measured with a wall mounted stadiometer. They were weighed on a standard set of Avery scales and their tibial length was measured with a tape measure applied between the lateral condyle and the lateral malleolus. The mean age of the volunteers was 19.2 years (± 1.2 years), mean height 172.1 cm (± 9.0cm) and mean body mass 69.3 kg (± 13.1kg). The mean length of femur was 40.3cm (± 2.4cm) and the mean length of tibia was 42.7cm (± 3.0cm). Details of the volunteers are summarised in Table1a. As can been seen there was relatively little variation in age and height of the volunteers. Seven volunteers dropped out (two males and five females) during the training period. Various reasons for the drop out were given. Four were attributed to personal time factors (exams, vacations); three volunteers had injuries, which were not related to the project. Thus eighteen males and ten females completed the whole programme. They are identified in table 1a.

The design of the experiment was reviewed and approved by the University of Glasgow Research Ethics Committee. Each volunteer was informed of the purpose of the study, the extent of their involvement, the materials and equipment used and any risks associated with the experiment. Volunteers were also made aware of their right to terminate participation at any time and without penalty and were encouraged to ask questions during any part of the study. Each expressed their understanding by signing a statement of informed consent. The consent form is shown in Appendix 1. Each volunteer completed details of the submission and a medical questionnaire in order to screen for any health problems, which could pose a risk during the testing procedure. The details and questionnaire is shown in Appendix II.

The first group of seven volunteers was recruited in October 1999. They were unpaid. But a second group of volunteers was recruited in March 2000. In this group, each volunteer was paid expenses of £5 per week to cover the costs of their participation in the project.

Table 1a. Characteristics of volunteers who completed the training study.

Subject	Sex	Age (Year)	Height (cm)	Weight (kg)	Length of femur (cm)	Length of tibia (cm)	Activity
1	F	20	162.3	54.5	40	40	C/U
2	F	18	166.8	55.5	36	39	C/U
3	F	18	160.6	57	37	42	D
4	F	20	168.4	59.1	41	42	C/U
5	F	18	168	61.5	40	42	D
6	F	18	154.4	61.7	38	36	R
7	F	19	170.1	64.6	42	44	R
8	F	18	166.5	65.8	45	40	R
9	F	20	167.8	67.5	41	41	R
10	F	20	168.5	68	42	40	R
11	M	20	181.5	66.8	45	45	R
12	M	22	178	68.5	38	46	C/U
13	M	18	171.6	68.7	41	43	R
14	M	18	181.6	71	40	47	R
15	M	19	180	80.9	41	45	C/U
16	M	20	185.3	83.6	40	45	C/U
17	M	20	186.5	85	39	47	N
18	M	19	179.2	108	40	45	R

Table 1b.Characteristics of volunteers who did not complete the training study.

Subject	Sex	Age (years)	Height (cm)	Weight (kg)	
19	F	20	169	64	I
20	F	19	156	54	I
21	F	18	166	68	V
22	F	18	165	60	T
23	F	18	167	60	E
24	M	20	1.64	69	I
25	M	21	168	65	E

Table 1a: This shows the characteristics of volunteers who completed the training study. Within each part of the table the volunteers are ordered by body weight. Initial activity level is indicated by R: recreational activity, C/U: competes for club or university, D: competes at district level, N: national level. Table 1b: This shows the characteristics of volunteers who did not complete the training study. The reason drop out was indicated by I: injury, V: vacation, T: travelling, E: exam.

The design of the study required an initial visit to the laboratory for familiarisation with equipment, the nature of the tests, an explanation of the training and completion of questionnaires and consent forms. There was then an initial set of anthopometric measurements, measurements of muscle force using the isokinetic dynamometer and measurements of knee extension velocity.

The author accompanied the volunteer to the university gymnasium where the training programme was explained and the training loads were set. Details of this are given later this section. All volunteers completed all training sessions. This was confirmed by examination of each individual's diary kept to record these training activities.

The volunteers were then left to follow the training programme for two weeks. They then returned to the lab for a second set of force and velocity measurements. This pattern of two weeks training followed by laboratory tests was repeated until four sets of tests were completed after 6 weeks training.

Laboratory - experimental testing procedure.

The testing procedures took place in the Kelvin Building Laboratories of the University of Glasgow. Each testing session lasted about 40 minutes. The sessions took place at intervals of 2 weeks. Each session occurred at the same time each day. They were advised to keep similar patterns of physical activity on the day proceeding the test sessions. The laboratory tests were conducted at the same time each testing day to minimise any diurnal effects on performance. In addition, the volunteers were asked to maintain their normal patterns of activity to minimise interactions with other activities of a potentially fatiguing nature. On the test day, they arrived at the laboratory and changed into shorts and a T-shirt. They warmed up by cycling on an exercise bicycle for 5 minutes before moving to the Kin Com dynamometer. The volunteer sat securely on the chair and adjustments were made to the horizontal position of the seat and the vertical position of the motor to align their knee joint with the axis of rotation of Kin Com. Accurate alignment was confirmed by observing minimum displacement of the limb when the knee was extended. When this

was done the volunteer was securely strapped in place with Velcro bands to minimise movement. This can be seen in figure 2.

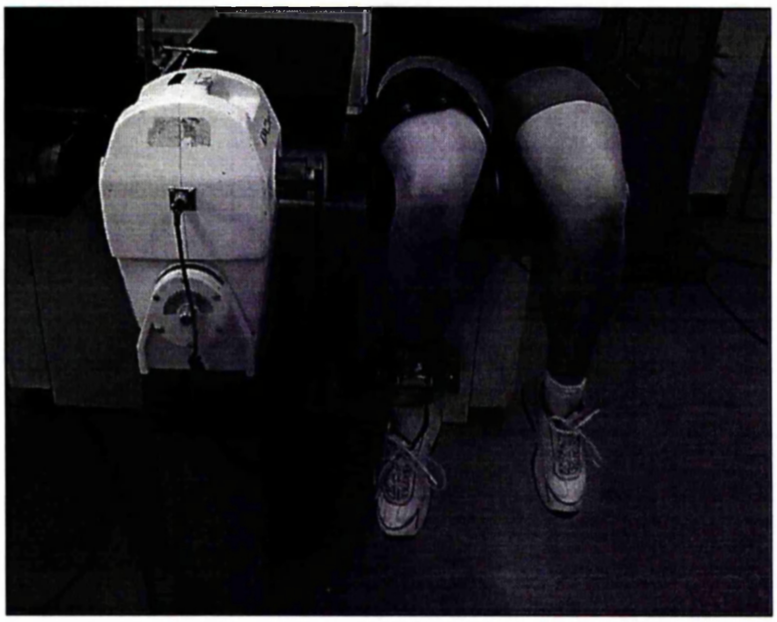


Figure 2. A volunteer seated in the KIN COM dynamometer.
Note the alignment of the knee and the axis of rotation of the machine.

The Kin Com software can compensate for changes caused by the weight of the lower limb as the knee is fully extended. This gravity compensation feature was used in all recordings.

Figure 3. Shows the volunteer with their right knee fully extended. The automatic gravity compensation allows for changes in torque due to change in position.

In each test, the volunteers warmed up with three easy contractions from 90 degrees of flexion to full extension. This allowed a check of the Kin Com functions. Then a series of maximal isometric contractions were made at 70° and 60° of flexion. These angles were chosen because they are close to the optimum position for force development at the knee (Caiozzo et al 1981). The shin pad was placed in a comfortable position low on the limb. This is illustrated in figure 3. The position was consistent between tests. Each of these contractions lasted 3 seconds and was followed by rest intervals of 30 seconds. After a series of sub-maximal isokinetic contractions had been made to familiarise the volunteer, 3 maximal isokinetic knee extensions at 60 degrees/second and 180 degrees/second were made. During each contraction the knee extended from 90° of flexion to a fully extended position.

All data were saved on the computer hard drive. The maximal effort in each case was identified and used for analysis. Figure 4 shows specimen data.

Leg press tests

Prior to the initiation of the next test, the volunteers were rested for 2min and during this time goniometers were attached over left knee joint and left ankle joint on the lateral side. This is illustrated in figure 6. The electrogoniometers (Penny & Giles Ltd, Christchurch, UK), record the range of movement of joints. They are easy to use because they simply cross the joint without requiring alignment with the axis of rotation. The electrogoniometer signals were amplified before being digitised at 100 Hz by a Pico Technologies ADC 11 analogue to digital converter (Pico Technologies, Cambridge, England) and Picoscope software.

The goniometers were calibrated against a range of angles marked out by a protractor. The voltage output recorded after digitisation was plotted against the protractor angle as shown in figure 5.

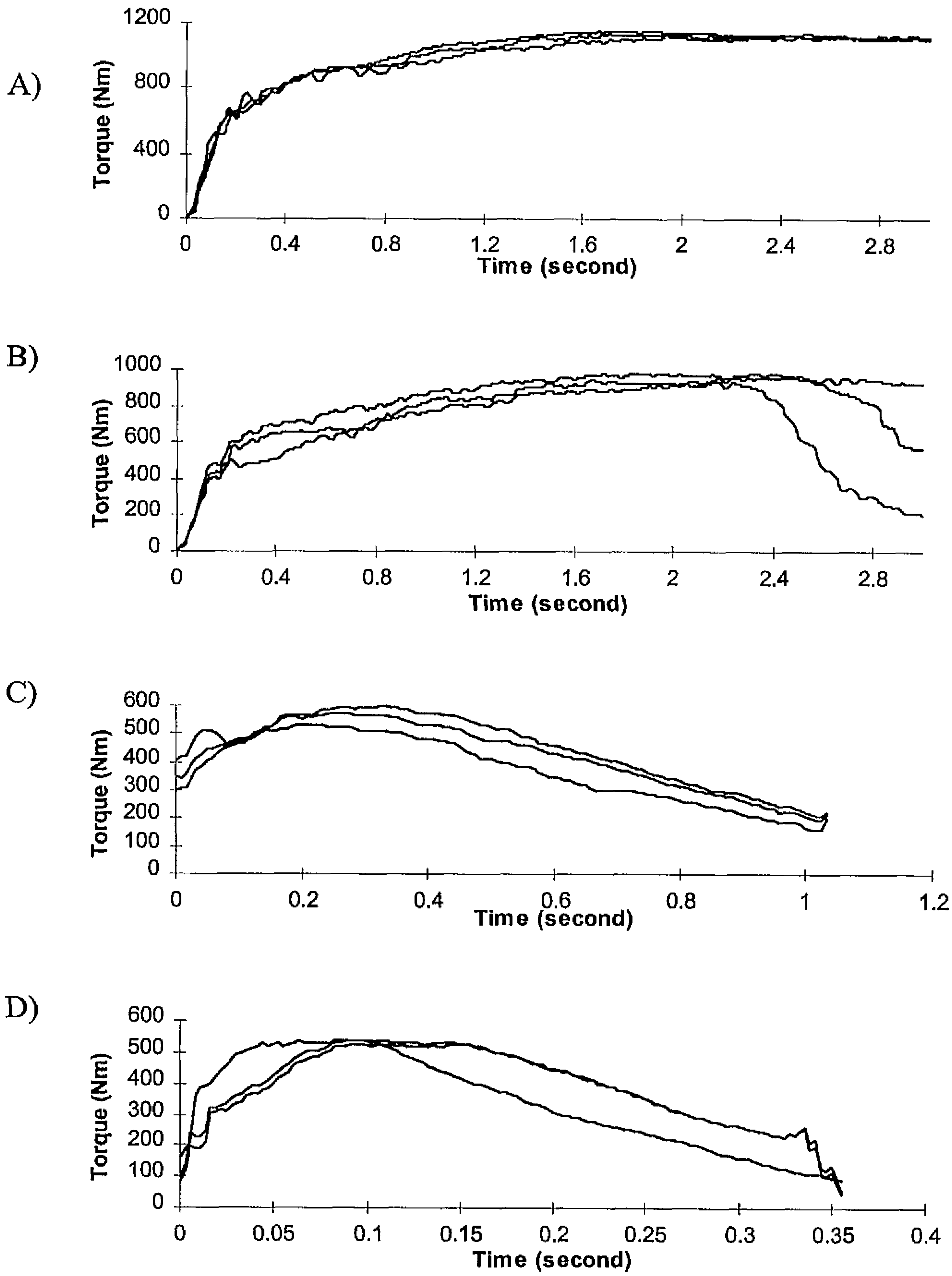


Figure 4. Sample graphs, which best represent, the Kin Com data. A) Show isometric contractions at 70 degrees of flexion. B) Show isometric contractions at 60 degrees of flexion. C) Shows isokinetic contractions at 60 degrees/sec. D) shows isokinetic contractions at 180 degrees/sec.

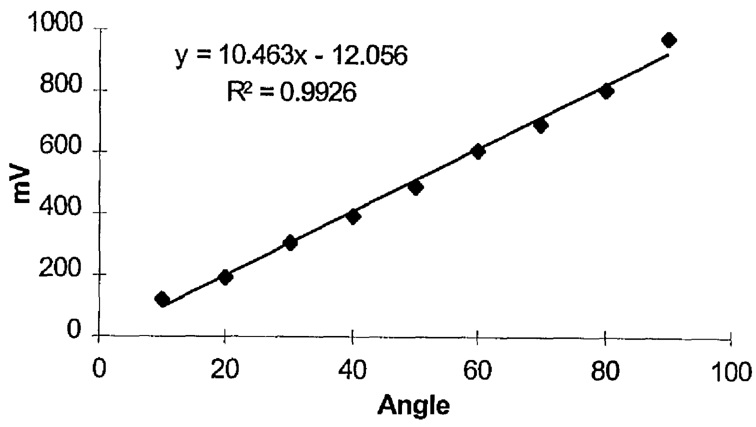


Figure 5. A calibration curve for an electrogoniometer.

The system was highly linear and allowed resolution of joint angle better than one degree. A typical record is shown in figure 7. This shows the ankle angle as the upper trace and the knee angle as the lower trace.

The volunteer made three full leg extension movements on the leg press machine. The trace shows a larger range of movement at the knee than at the ankle joints in the downward direction.

A)

B)

C)

Figure 6. Placement of surface electrogoniometers used in the present study. A) The goniometer is shown on the lateral view of the left ankle joint. B) Goniometer on the lateral side of the knee joint. B) Show fully the lower limb positions.

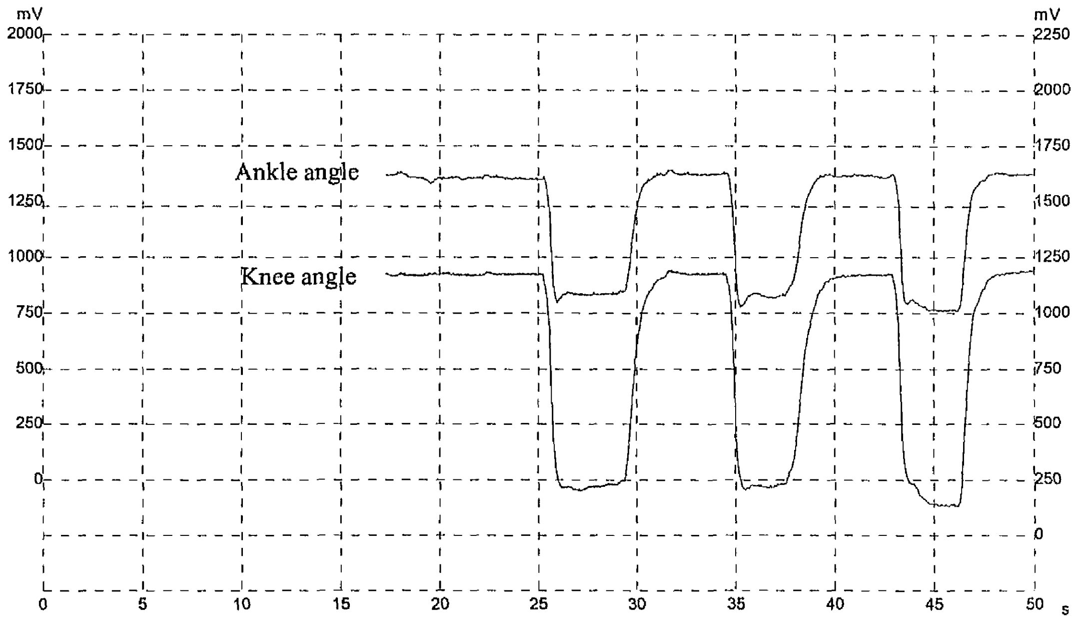


Figure 7. A typical Picoscope recording showing the goniometer outputs when the volunteer made three leg extensions.

The volunteers lay supine in the leg press machine as illustrated in figure 8. The headrest was adjusted to make the volunteer comfortable. Each volunteer placed their feet on the footplate at a position selected as optimal. This position was marked with tape to allow the position to be reproduced on subsequent days. In the starting position, the legs were flexed to approximately 60° at the hip 80° at the knee and dorsiflexed to 50° at the ankle. The volunteer then made a series of symmetrical leg extension movements from this position. These were initially gentle to familiarise them with the device then increased as the volunteer produced maximal efforts in response to encouragement.

The final three extensions were made with standard load. This was set at 80% of the maximum isometric torque at 70° of flexion from earlier tests on the Kin Com system. This allowed movements made under a significant load to be analysed. The goniometer signals during the maximal efforts were recorded on a laboratory computer.

The goniometer signals were digitised at a rate of 100 samples/sec. This did not limit the analysis of movements. Indeed it was necessary to smooth the raw data to allow calculation of maximal joint velocity and acceleration. After recording knee and ankle angles during limb extension in the leg press test an analysis of the instantaneous velocity was performed. This was done numerically using Excel 5 spread sheets to calculate changes in angle between successive time intervals. This process was repeated to calculate joint accelerations. This double differentiation gave rise to discontinuities and sharp changes in the calculated accelerations. To minimise these problems the velocity data were subjected to a 5 point smoothing process before the second calculation. An initial investigation used 3-point smoothing. This gave rather less satisfactory results than 5 point smoothing.

A)

B)

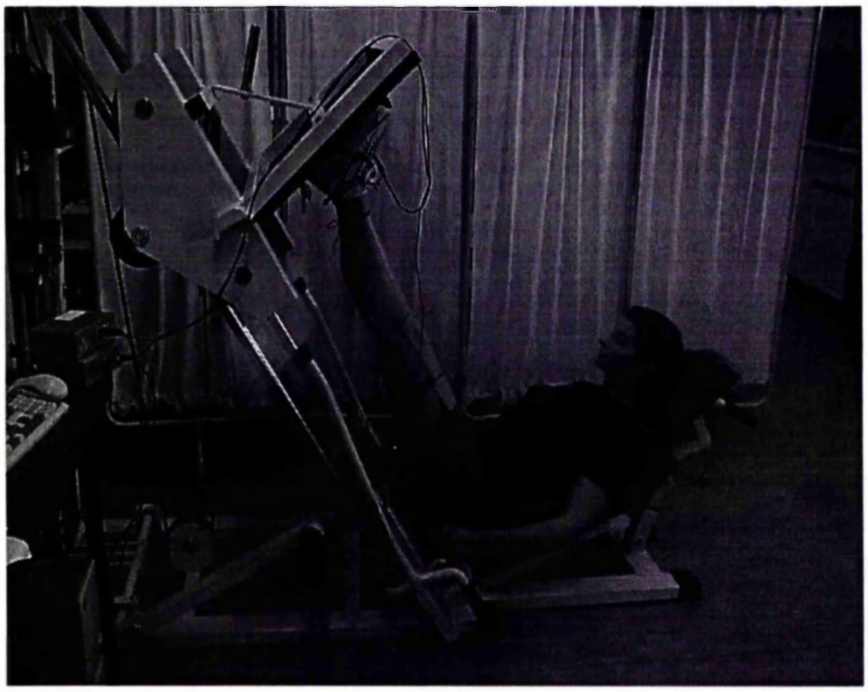


Figure 8. Shows, A) the volunteer was seated in the leg press machine in a semi reclining position. B) The volunteer has fully extended their legs.

Gymnasium-training section:

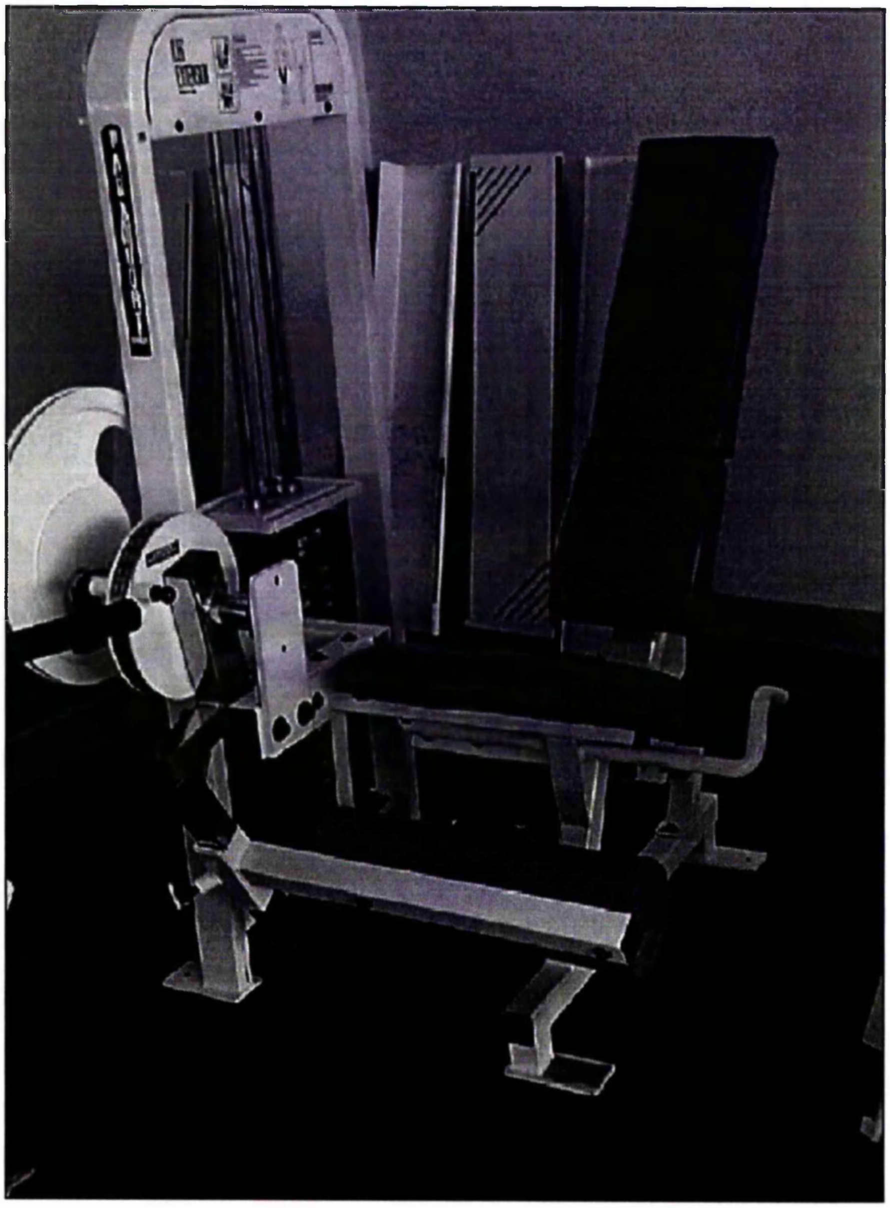
The experimenter accompanied volunteers to the gymnasium and explained the training exercises. The training programme included leg extension, leg curl and leg press exercises. Identifying the one repetition maximum load for that exercise set the load for each exercise. This then determined subsequent loads for repeated exercises. The standard training programme is shown in table 2.

LOAD	REPETITIONS	SETS
60%	4	3
	REST 2 MIN	
70%	3	3
	REST 2 MIN	
80%	2	3

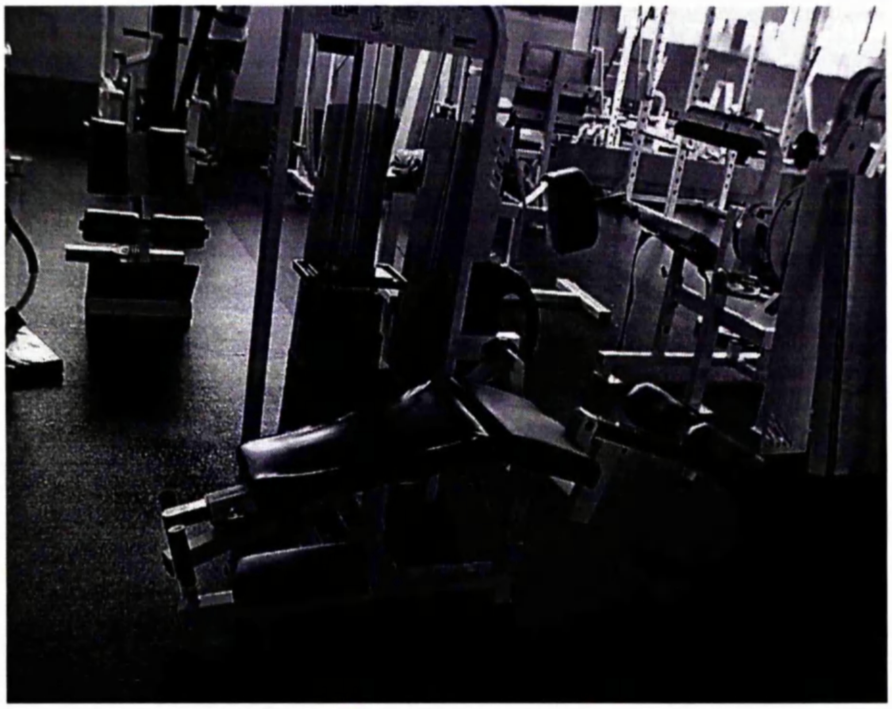
Table 2: This shows the typical training programme.

The volunteers completed six sessions of weight training exercises in the Stevenson Building over two weeks. They then returned to the laboratory for tests as described in section 3. At each laboratory session the training diary was inspected to check that training had been completed and any required changes to the load in any exercise were made. An increase in the load was necessary when leg muscles became stronger and the training load was reset accordingly. Alternatively, a decrease in the load might be needed if the load was still uncomfortable. After 6 weeks the volunteer completed the experiment. Figure 9 shows the machines used in these exercises.

A)



B)



C)

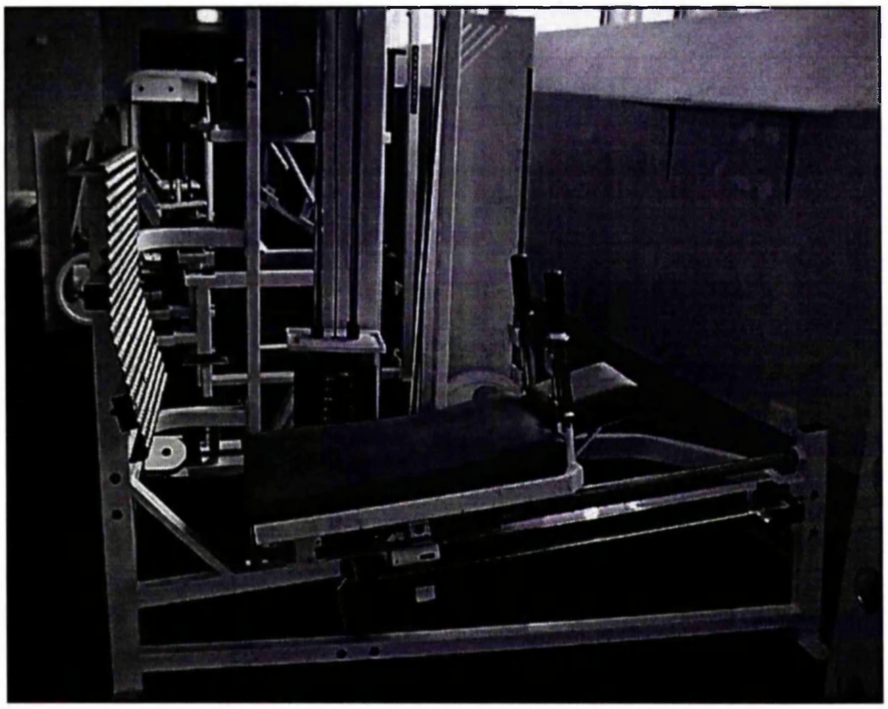


Figure 9. This shows the weight machines for training for lower limb. A) Leg extension machine. B) Leg curl machine. C) Leg press machine.

The force - velocity study

The participants in this study were students of the University of Glasgow. In total, twenty-five volunteers, ten females and fifteen males, all healthy and untrained, were randomly selected from physiology laboratory classes. The physical details of the volunteers are shown in Table 3. None of these volunteers had participated in the earlier study.

Laboratory class

The volunteers performed an initial warm up by cycling on an exercise bicycle for 5 minutes. Isometric knee extension torque was measured on the Kin Com following the protocol described earlier except that isometric forces were recorded over a wider range of knee joint angles. The torque measurements were made during three maximum contractions at 110°, 80°, 50° and 10°, of knee flexion.

The lifting exercises on the leg press machine were also similar except that the movements were recorded under a series of loads. Each volunteer began lifting with a load of 48kg. At each subsequent test the load was increased by 20 kg until the volunteer could no longer move the load. During each lift, the volunteer received strong verbal encouragement to ensure they made maximal efforts. Knee position was measured with Penny & Giles electrogoniometers as described before. The calculation of knee velocity was also described earlier.

Table 3. Characteristics of volunteers who completed the experiment study.

Volunteer	Sex	Age (year)	Height (cm)	Weight (kg)
26	F	20	161.4	53.7
27	F	21	157.4	55.5
28	F	20	161.6	55.6
29	F	20	157	58.4
30	F	20	171.3	60.7
31	F	21	166.8	61.8
32	F	21	171.3	62
33	F	20	168.1	63.7
34	F	19	171.6	65.5
35	F	21	167.1	82.2
36	M	21	169.3	56
37	M	21	166.2	64.7
38	M	20	185.5	66
39	M	21	171.2	68.7
40	M	20	171	72
41	M	23	175.7	72.9
42	M	20	175.4	78.5
43	M	21	185.5	79.2
44	M	21	184.2	80
45	M	21	179.5	80.4
46	M	20	177.9	85.8
47	M	20	185.7	88.2
48	M	19	182.3	88.4
49	M	23	173.5	90.4
50	M	20	180	107.2

Table 3: This shows the characteristics of volunteers who completed the experiment study. Within each part of the table the volunteers are ordered by body weight.

RESULTS

Two series of experiments were completed. The first series investigated changes in isometric torque and maximum knee and ankle extension velocities before and after a short period of training. The second series investigated the length tension characteristics of knee extensor muscles and knee extension velocity under a range of loads. Each series will be described in turn.

First series of experiments: Isometric recordings

		Age (Year)	**Height (cm)**	**Weight (kg)**	**Length of femur (cm)**	**Length of tibia (cm)**
All	**Range**	18 – 22	154 - 186	54 - 108	36 -45	36 - 47
	Mean	19.2	172.1	69.3	40.3	42.7
	SD	1.2	9.0	13.1	2.4	3.0
Males	**Range**	18 – 22	171 - 186	67 - 108	38 - 45	43 - 47
	Mean	19.5	180.5	79.1	40.5	45.4
	SD	1.3	4.6	13.8	2.1	1.3
Females	**Range**	18 – 20	162 - 170	54 - 69	36 - 45	36 - 44
	Mean	18.9	165.3	61.5	40.2	40.6
	SD	1.0	4.8	4.9	2.7	2.2
T test	**F vs. M**	0.152	0.001	0.004	0.400	0.001

Table 4. Physical characteristics of the volunteers who completed the study.

The details of the volunteers who completed the first series of experiment are shown in Table 1. Significant differences in height and body weight and tibia length between males and females are shown in table 4. There are no significant differences in age between men and women.

In these experiments the maximum of right knee extension torque was measured at 70° and 60° of flexion. These data are shown in tables 5 and 7. At the initial visit, when tested at 70° of knee flexion, a range of knee extension torques between 508 - 1290 Nm was found. The mean torque was 814.9 ± 223.8 Nm. The mean for male volunteers was 981 ± 217 Nm. The female volunteers had a mean torque of 682 ± 118 Nm. The difference between males and females was significant ($P < 0.002$) when tested with a heteroscedastic T test.

When the volunteers returned for testing after two weeks training the maximum torque was measured again. These values are shown in column T2 of table 5. The torque had increased in all volunteers but one (volunteer 18). This overall increase was significant ($P< 0.0001$) when tested with a paired T test. The torque continued to increase in the third and fourth test sessions, i.e. after 4 and 6 weeks of training. These values are shown in columns T3 and T4.

The column T4-T1 showed the values of mean torque increase from the start to the finish was for all volunteers 172.7 ± 115.9 Nm. A paired T test showed the increase was significant ($P <0.0001$). When the analysis was repeated for the male volunteers, the mean torque increase was 205 ± 148.8 Nm. This increase was significant ($P <0.006$). The increase in torque for the female volunteers was 146.9 ± 80.5 Nm. This also was significant ($P <0.0003$). These results are shown graphically in Figure 10.

The knee joint extension torque was normalised by dividing by the initial body weight of each volunteer. Male volunteers were significantly heavier than women volunteers (table 4). Dividing the knee extension torque by body weight is an attempt to provide a fairer comparison between the sexes. These data are shown in Table 7. Even when the data have been adjusted, the males still develop significantly more torque than the females ($P < 0.00001$). Both groups increase their torque/kilo significantly between the initial and the final tests ($P< 0.004$ males, $P<0.0002$ females). These data are illustrated in figure 11.

In addition, the data shown in table 5 show that in the initial and final tests, the males were significantly stronger than the females. However, in the isometric tests at 70 degrees both groups increased their performance by approximately 21%.

	Volunteer	T1(Nm)	T2(Nm)	T3(Nm)	T4(Nm)	T4-T1(Nm)
F	5	508	565	569	640	132
F	7	577	704	800	864	287
F	2	589	611	679	713	124
F	3	637	639	741	743	106
F	4	643	738	757	852	209
F	1	705	839	801	860	155
F	8	721	748	732	700*	-21*
F	9	752	835	853	864	112
F	6	767	828	868	965	198
F	10	920	1024	1060	1087	167
M	11	749	926	925	989	240
M	12	792	846	949	891	99
M	13	857	961	1058	1156	299
M	14	875	1088	1024	1213	338
M	15	881	1034	1129	1181	300
M	18	1134	1033*	1101*	1016*	-118*
M	16	1271	1391	1375	1518	247
M	17	1290	1448	1507	1525	235

All	**Mean**	814.9	903.2	940.4	987.6	172.7
	SD	223.8	242.5	240.3	255.7	115.9
	T test		0.001	0.001	0.0001	
Males	**Mean**	981.1	1090.9	1133.5	1186.1	205.0
	SD	216.8	216.5	205.0	233.5	148.8
	CI					103.1
	T test		0.016	0.002	0.006	
Females	**Mean**	681.9	753.1	786.0	828.8	146.9
	SD	117.5	135.1	129.5	134.3	80.5
	T test		0.001	0.0002	0.0003	

Table 5. Shows the isometric extension torque with the knee joint at 70° of flexion for all volunteers, test by test. The summary panels show mean and standard deviations for all volunteers and for male and female volunteers separately. The t test cells show the results of paired T tests between the initial value at the first test (T1) and subsequent tests.
* Indicates values which are less than the initial T1 value.

Similar experiments were repeated on the same volunteers with the knee at 60 degrees of flexion. These data are shown in tables 8 and 9. These are absolute values, i. e. uncorrected for body weight. At the initial test the range of torque was between 373-1095 Nm. The mean torque was 674.6 $\pm$ 185.5 Nm. The male volunteers mean was 796.1 $\pm$ 192.9 Nm. The mean for female volunteers was 577.4 $\pm$ 111.5 Nm. The difference between males and females was significant ($P < 0.008$) when tested with a heteroscedastic T test.

When the volunteers returned for testing after two weeks training the maximum torque was measured. The values are shown in column T2 in table 8. The torque had increased in all volunteers but one volunteer (volunteer 18). This overall increase was significant ($p < 0.0001$) when tested with a paired T test. The torque continued to increase in the third and fourth test sessions.

The column T4-T1 shows the values of mean torque for all volunteers increase was 141.7 $\pm$ 114.6 Nm. A paired T test showed the increase was significant ($P < 0.0001$). When the analysis was repeated for the male volunteers, the mean torque increase was 163.9 $\pm$ 161.3 Nm. This increase was significant ($P < 0.02$). The increase in torque for the female volunteers was 123.9 $\pm$ 61.4 Nm. This also was significant ($P < 0.0001$). These results are shown graphically in figure 12.

The knee joint torque was divided by the initial body weight of each volunteer to calculate torque/kilo. These data are shown in Table 9. Even when the data have been adjusted for the effects of body size, the males still develop significantly more torque than the females ($P < 0.00001$). Both groups increase their torque/kilo significantly ($P < 0.02$ males, $P < 0.0001$ females) between the initial and the final tests. These data are illustrated in figure 13. Only one volunteer showed a reduction in torque/kilo.

In addition, in the initial and final tests the males were significantly stronger than the females. However, in the isometric tests at 60 degrees of flexion both groups increased their performance by approximately 21%.

A series of test / retest measurements were made to investigate if increasing torques could be caused by familiarity with experiment at the second visit. During these tests five adult volunteers visited the laboratory twice. There was at least one week between visits and no training sessions were interposed between the two visits. At each visit they made a series of maximal isometric contractions. The peak torques was recorded and compared using paired T tests. Data for tests at 70° of knee joint flexion are shown in table 6. No significant difference was observed.

Sex		**T1(N/m)**	**T2(N/m)**	**T2-T1(N/M)**
M	A	1290	1350	60
M	B	1420	1350	-70
M	C	1190	1230	40
M	D	1280	1320	40
M	E	1180	1240	60

mean		1272.00	1298.00	26.00
SD		96.80	58.91	54.59
T test			0.35	

Table 6. Shows the isometric torque at 70° of knee joint flexion for volunteers with no training programme.

A)

B)

C)

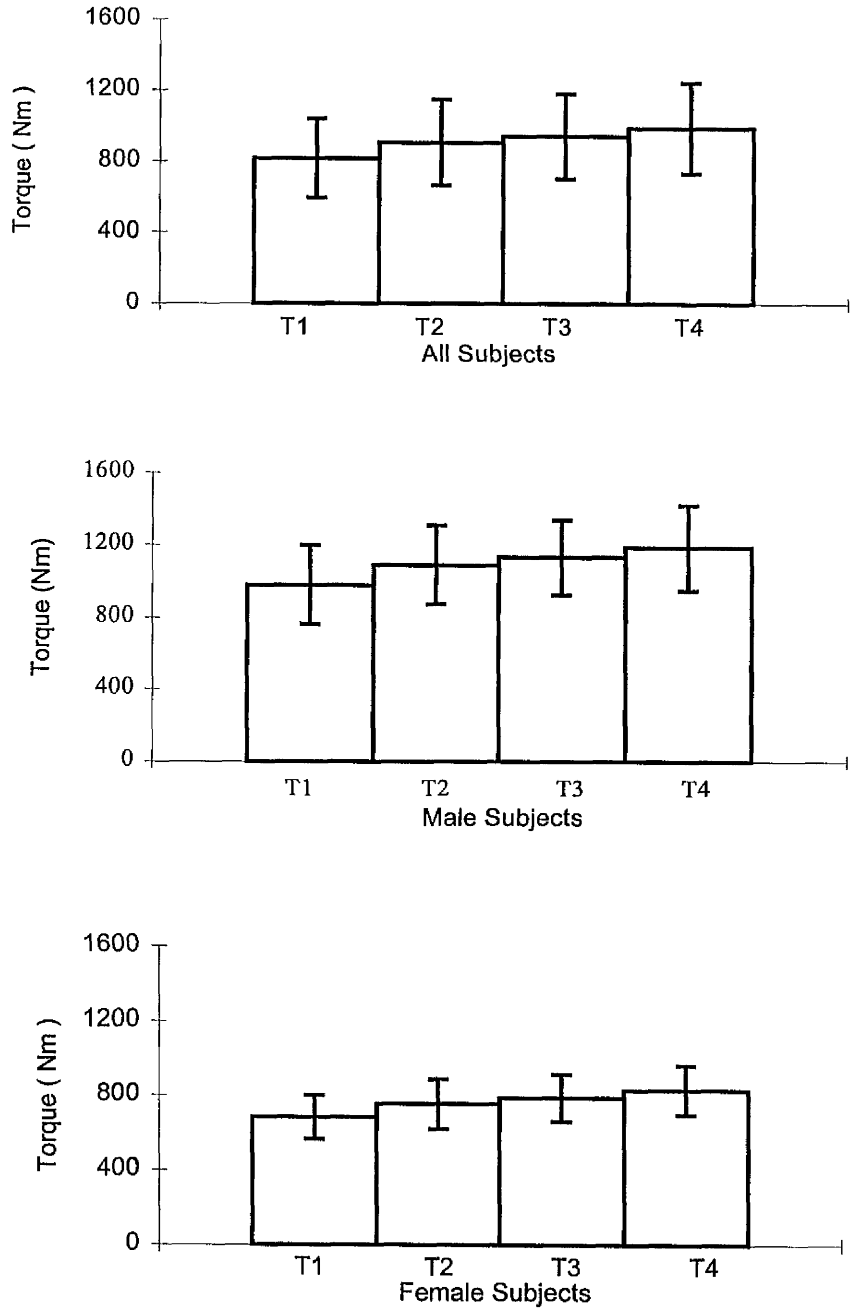


Figure 10. Mean and standard deviations of isometric extension torque recorded at 70° of knee joint flexion before and after training for A) all volunteers, B) male volunteers and C) female volunteers. The first test results are on the left and the final test on the right. The torque increases are significant when tested with paired T tests, A ($P < 0.0001$), B ($P < 0.01$), C ($P < 0.001$).

		T1(Nm/kg)	T4(Nm/kg)	T4-T1(Nm/kg)
F	5	8.26	10.41	2.15
F	7	8.93	13.37	4.44
F	2	10.61	12.85	2.23
F	3	11.18	13.04	1.86
F	4	10.88	14.42	3.54
F	1	12.94	15.78	2.84
F	8	10.96	10.64*	-0.32*
F	9	11.14	12.80	1.66
F	6	12.43	15.64	3.21
F	10	13.53	15.99	2.46
M	11	11.21	14.81	3.59
M	12	11.56	13.01	1.45
M	13	12.47	16.83	4.35
M	14	12.32	17.08	4.76
M	15	10.89	14.60	3.71
M	18	10.50	9.41*	-1.09*
M	16	15.20	18.16	2.95
M	17	15.18	17.94	2.76

All	**Mean**	11.68	14.26	2.59
	SD	1.81	2.55	1.54
	T test		0.00001	
Males	**Mean**	12.42	15.23	2.81
	SD	1.84	2.96	1.88
	T test		0.004	
Females	**Mean**	11.09	13.49	2.41
	SD	1.64	1.99	1.28
	T test		0.0002	

Table 7. Shows the isometric torque of the knee at 70° of flexion for all volunteers test by test. The summary panels show mean and standard deviations for all volunteers of body weight and for male and female volunteers separately. The t test cells show the results of tests between the initial value at the first test (T1) and subsequent tests.

* Indicates values which are less than the initial T1 value.

A)

B)

C)

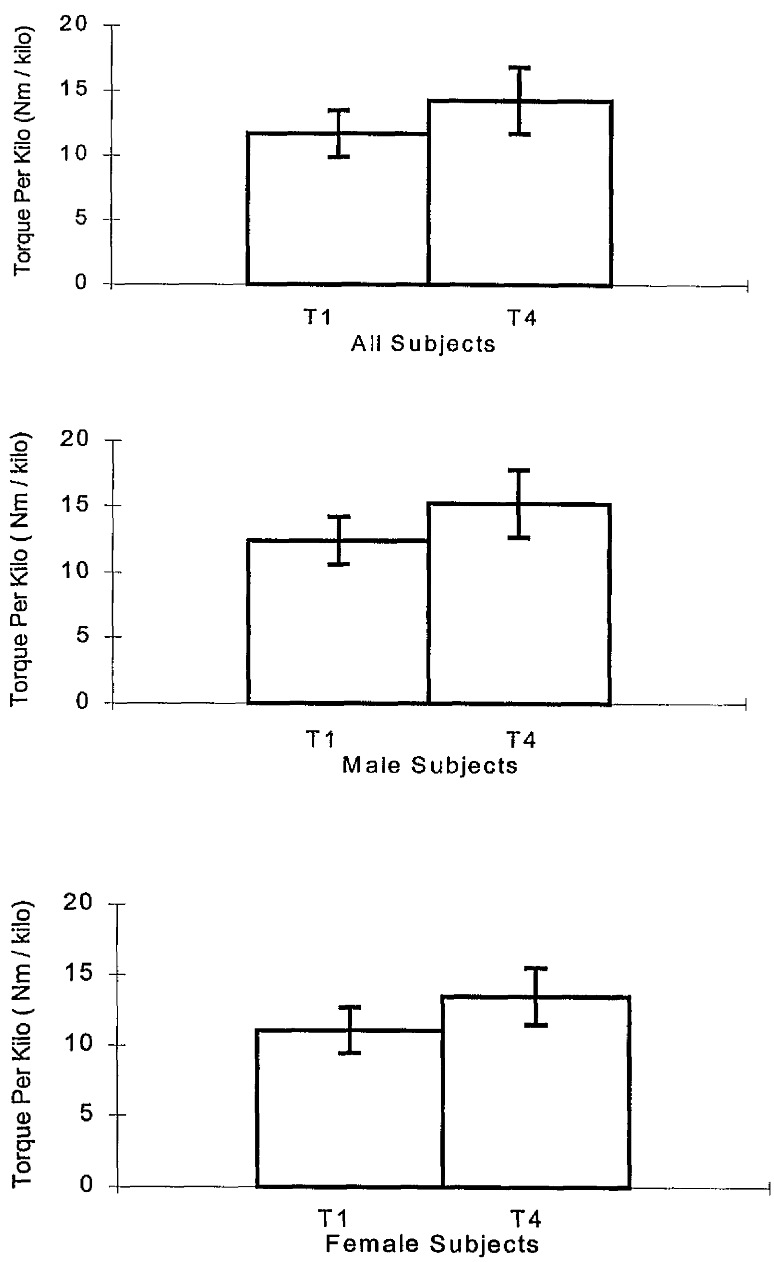


Figure 11. Mean and standard deviations of isometric knee extension torque recorded at 70° of flexion before and after training for A) all volunteers, B) male volunteers and C) female volunteers. The torque is normalised and expressed as torque per kilo body weight. The initial test results are shown on the left and the final test results are shown on the right. The torque increases are significant when tested with paired T tests, A ($P < 0.0001$). B ($P < 0.001$). C ($P < 0.0001$).

		T1(Nm)	T2(Nm)	T3(Nm)	T4(Nm)	T4-T1(Nm)
F	5	373	436	427	485	112
F	2	466	564	583	607	141
F	3	527	545	605	605	78
F	4	547	584	656	745	198
F	7	577	616	697	785	208
F	9	592	686	753	720	128
F	6	620	649	720	798	178
F	1	625	645	638	720	95
F	8	663	688	755	760	97
F	10	784	816	834	788	4
M	11	576	781	841	844	268
M	12	640	676	831	672	32
M	13	675	836	892	981	306
M	15	684	871	950	1024	340
M	14	743	901	861	963	220
M	18	946	794*	845*	821*	-125*
M	17	1010	1229	1217	1230	220
M	16	1095	1099	1015	1145	50

All	**Mean**	674.6	745.3	784.4	816.3	141.7
	SD	185.5	196.8	179.7	190.9	114.6
	T test		0.004	0.0003	0.0001	
Males	**Mean**	796.1	898.4	931.5	960.0	163.9
	SD	192.9	180.6	131.5	180.2	161.3
	T test		0.060	0.035	0.024	
Females	**Mean**	577.4	622.9	666.8	701.3	123.9
	SD	111.5	101.5	113.6	102.7	61.4
	T test		0.001	0.0001	0.0001	

Table 8. Shows the isometric knee extension torque of the knee at 60° of flexion for all volunteers test by test. The summary panels show mean and standard deviations for all volunteers and for male and female volunteers separately. The t test cells show the results of tests between the initial value at the first test (T1) and subsequent tests.
* Indicates values which are less than the initial T1 value.

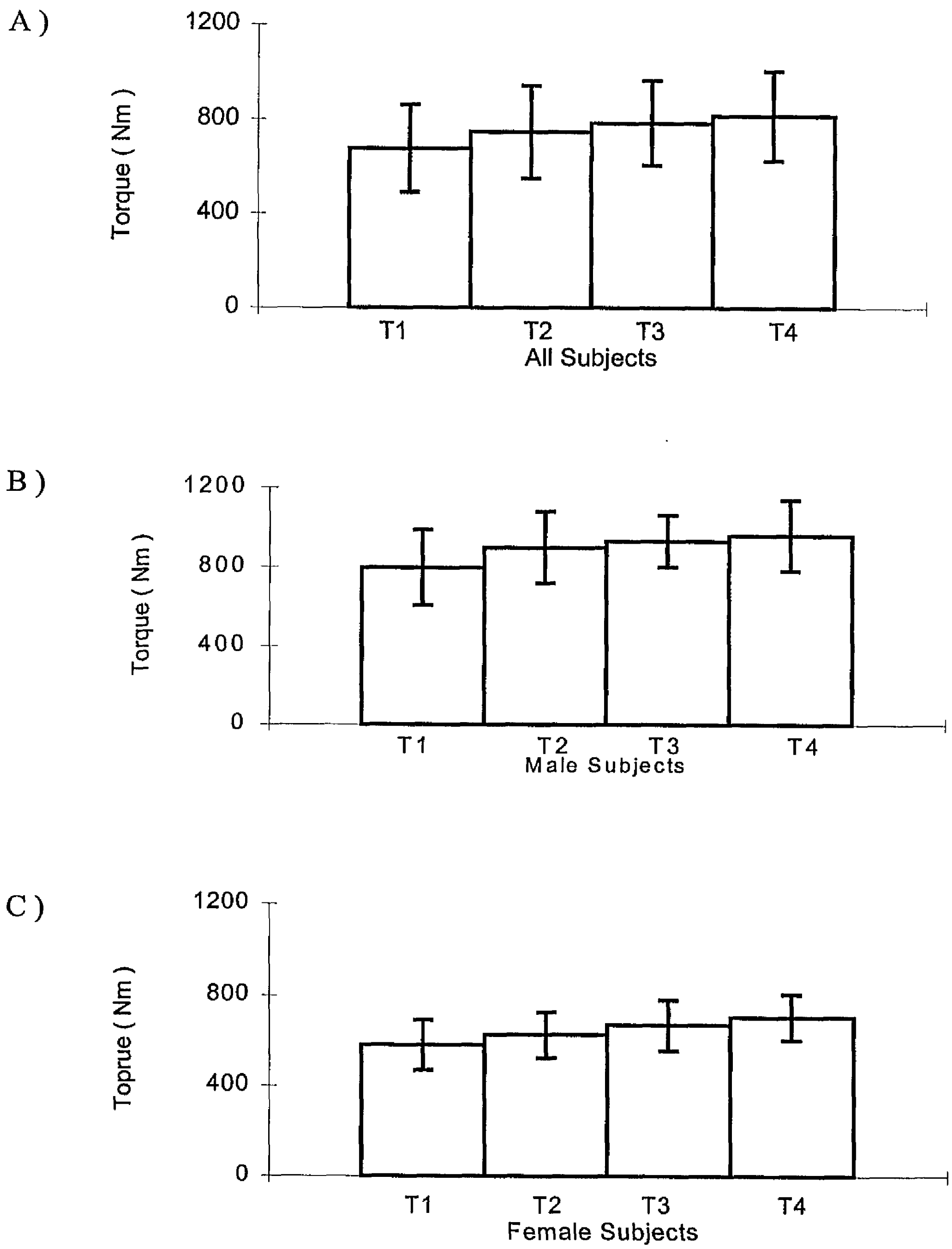


Figure 12. Mean and standard deviations of isometric knee extension torque recorded at 60° before and after training for A) all volunteers, B) male volunteers and C) female volunteers, figures in each the mean values for the initial test are shown on the left and the final test on the right. The torque increases are significant when tested with paired T tests, A ($P < 0.0001$). B ($P < 0.02$). C ($P < 0.001$).

		T1(Nm/kg)	T4(Nm/kg)	T4-T1(Nm/kg)
F	5	6.07	7.89	1.82
F	2	8.40	10.94	2.54
F	3	9.25	10.61	1.37
F	4	9.26	12.61	3.35
F	7	8.93	12.15	3.22
F	9	8.77	10.67	1.90
F	6	10.05	12.93	2.88
F	1	11.47	13.21	1.74
F	8	10.08	11.55	1.47
F	10	11.53	11.59	0.06
M	11	8.62	12.63	4.01
M	12	9.34	9.81	0.47
M	13	9.83	14.28	4.45
M	15	8.45	12.66	4.20
M	14	10.46	13.56	3.10
M	18	8.76	7.60*	-1.16*
M	17	11.88	14.47	2.59
M	16	13.10	13.70	0.60

All	**Mean**	9.7	11.8	2.1
	SD	1.6	2.0	1.5
	T test		0.000	
Males	**Mean**	10.1	12.3	2.3
	SD	1.7	2.4	2.1
	T test		0.02	
Females	**Mean**	9.4	11.4	2.0
	SD	1.6	1.5	1.0
	T test		0.0001	

Table 9. Shows the isometric extension torque expressed per kilo body weight with the knee joint at 60° of flexion at the initial and final tests. The summary panels show mean and standard deviations for all volunteers and for male and female volunteers separately. The t test cells show the results of tests between the initial value at the first test (T1) and subsequent tests. The last columns show the difference between initial and final values.

* Indicates values which are less than the initial T1 value.

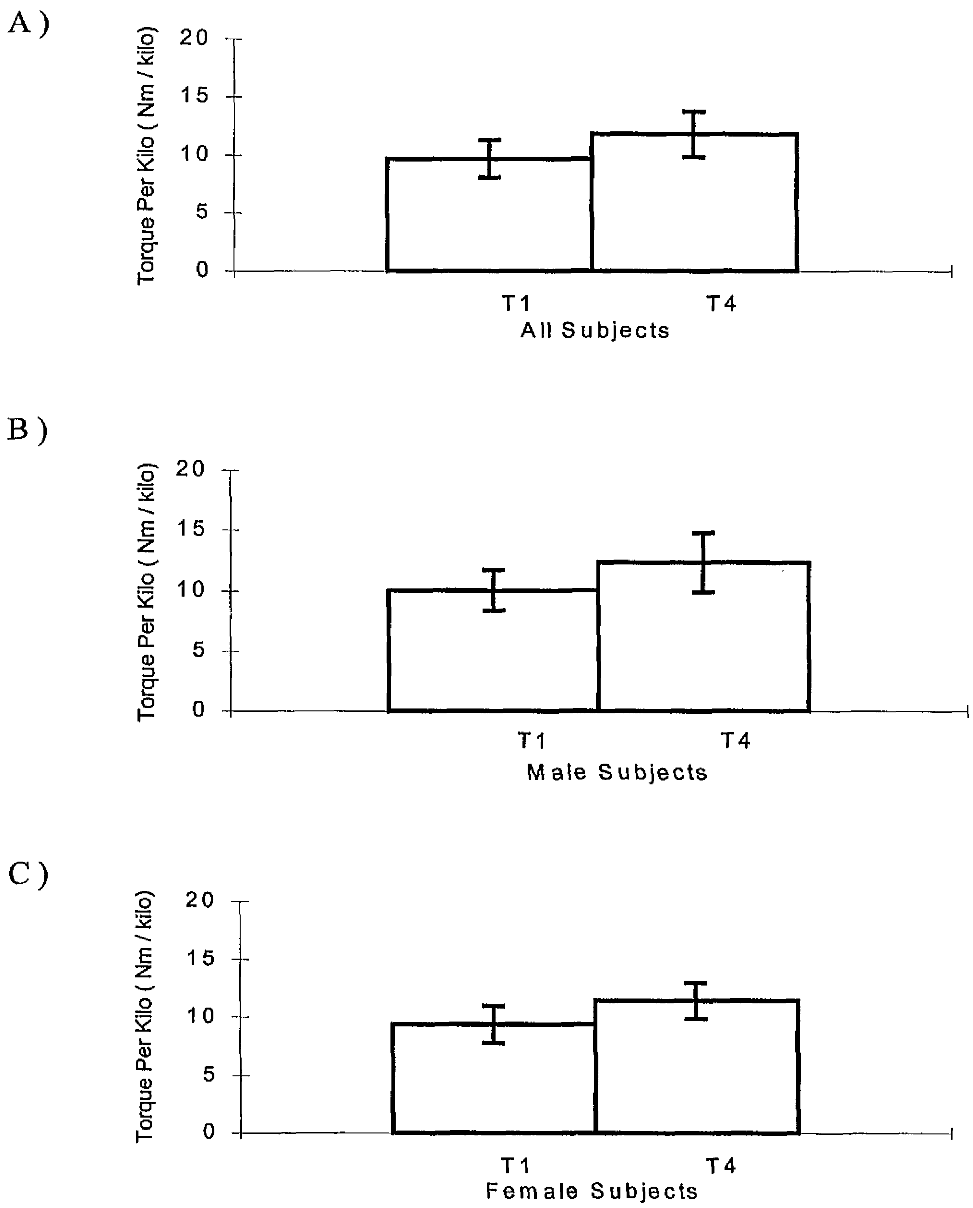


Figure 13. Mean and standard deviations of isometric knee extension torque recorded 60° of flexion before and after training for A) all volunteers, B) male volunteers and C) female volunteers. The torques is normalised and expressed are torque per kilo body weight. The torque increases are significant when tested with paired T tests (A $P < 0.00001$, B $P < 0.02$, C $P < 0.0001$).

Isokinetic recordings

Recordings of peak knee extension torque during isokinetic movements at 60 degrees/second and 180 degrees/second were also made. These data are shown in tables 10 and 11. In the first tests at 60 degrees/second, the range of maximum torque was 418 - 920 Nm. The mean torque was 617.8 ± 148.7 Nm. The mean for male volunteers was 746.1 ± 114.4Nm. The female volunteers had a mean torque of 515.1 ± 72.2 Nm. The difference between males and females was significant ($P < 0.0001$) when tested with a heteroscedastic T test.

When the volunteers returned for testing after two weeks training the maximum torque was measured again. These values are shown in column T2 in table 10. The torque had increased in 13 volunteers. This overall increase was small and not significant at $P < 0.05$ when tested with a paired T test. The torque continued to increase in the third and fourth test sessions, i.e. after 4 and 6 weeks of training. These values are shown in the columns T3 and T4.

The column T4-T1 showed the values of mean torque increase in all volunteers. The mean overall increase was 106.4 ± 105.6 Nm. A paired T test showed the increase was significant ($P < 0.0005$). When the analysis was repeated for male volunteers, the mean torque increase was 145.4 ± 123.3 Nm. This increase was significant ($P < 0.01$). The increase in torque for the female volunteers was 75.3 ± 82.7 Nm. This also was significant ($P < 0.02$). These results are shown graphically in figure 14.

		T1(Nm)	T2(Nm)	T3(Nm)	T4(Nm)	T4-T1(Nm)
F	1	418	592	653	670	252
F	3	418	425	473	483	65
F	2	450	520	526	568	118
F	7	478	509	505	514	36
F	5	536	545	649	671	135
F	4	540	575	532*	614	74
F	9	541	510*	469*	522*	-19*
F	8	542	554	518*	512*	-30*
F	6	599	577*	589*	698	99
F	10	629	663	655	652	23
M	11	597	602	685	692	95
M	12	620	619*	787	752	132
M	13	685	819	896	879	194
M	16	713	999	1082	1029	316
M	14	754	806	891	989	235
M	15	821	816*	881	919	98
M	18	859	695*	841*	760*	-99*
M	17	920	1075	1153	1112	192

All	**Mean**	617.8	661.2	710.3	724.2	106.4
	SD	148.7	176.2	208.4	190.2	105.6
	T test		0.075	0.003	0.0005	
Males	**Mean**	746.1	803.9	902.0	891.5	145.4
	SD	114.4	168.5	151.2	148.6	123.3
	T test		0.264	0.008	0.012	
Females	**Mean**	515.1	547.0	556.9	590.4	75.3
	SD	72.2	62.9	73.7	79.9	82.7
	T test		0.115	0.160	0.018	

Table 10. Shows the isokinetic knee extension torque at 60°/sec for all volunteers test by test. The summary panels show mean and standard deviations for all volunteers, for male and female volunteers separately. The t test cells show the results of tests between the initial value at the first test (T1) and subsequent tests.

* Indicates values which are less than the initial T1 value.

The knee extension torque was divided by the initial body weight of each volunteer to calculate torque/kilo. These data are shown in Table 11. Even when the data have been adjusted for the effects of body size, the males still develop significantly more torque than the females ($P < 0.0003$). Both groups increased their torque/kilo significantly ($P < 0.007$ males, $P < 0.02$ females) between the initial and the final tests. The mean torque increase for all volunteers was 1.58 ± 1.47 Nm/kg. A paired T test showed the increase was significant ($P < 0.0003$). When the analysis was repeated for the male volunteers, the mean torque increase was 1.98 ± 1.47 Nm/kg. This increase was significant ($P < 0.007$). The increase in torque for the female volunteers was 1.27 ± 1.48 Nm/kg. This also was significant ($P < 0.02$). This data are illustrated in Figure 15.

In addition, in both the initial and final tests the males were significantly stronger than the females. However, in the isokinetic tests at 60°/s both groups increased their performance by approximately 19% (male) and 15% (female).

Similar experiments were repeated on the same volunteers with the knee velocity at 180 degrees/second. These data are shown in tables 12 and 13. At the first test the range of maximum torque was 287 - 905 Nm. The mean torque for male volunteers was 639.9 ± 141 Nm. The female volunteers had a mean torque of 433.4 ± 76.7 Nm. The difference between males and females was significant ($P < 0.001$) when tested with a heteroscedastic T test.

When the volunteers returned for testing after two weeks training the maximum torque was measured. These values are shown in column T2 in table 12. The torque had increased in 14 volunteers. This overall increase was significant ($P < 0.003$) when tested with a paired T test. The torque continued to increase in the third and fourth test sessions, i.e. after 4 and 6 weeks of training. These values are shown in column T3 and T4. The column T4-T1 showed the values of mean torque increases for all volunteers by 117.8 ± 89.8 Nm. A paired T test showed the increase was significant ($P < 0.001$). When the analysis was repeated for the male volunteers, the mean torque increase was 172.9 ± 103.3 Nm. This increase was significant ($P < 0.002$). The increase in torque for the female volunteers was 73.7 ± 45.6 Nm. This also was significant ($P < 0.0006$). These results are shown graphically in Figure 16.

The knee joint extension torque at 180°/s was divided by the initial body weight of each volunteer to calculate torque/kilo. These data are shown in Table13. The male volunteers increased their mean torque by 2.30 ± 1.41Nm/kg. This increase was significant ($P < 0.002$). The increase in torque for the female volunteers was 1.24 ± 0.82 Nm/kg. Even when the data has been adjusted for the effects of body size, the males still develop significantly more torque than the females ($P < 0.00001$). In the isokinetic tests at 180°/s both groups increased their performance. The males increased by 27% and the females by 17%.

		T1(Nm/kg)	T4(Nm/kg)	T4-T1(Nm/kg)
F	1	7.67	12.29	4.62
F	3	6.19	7.16	0.96
F	2	6.62	8.35	1.74
F	7	8.61	9.26	0.65
F	5	9.40	11.77	2.37
F	4	9.14	10.39	1.25
F	9	8.80	8.49*	-0.31*
F	8	8.78	8.30*	-0.49*
F	6	9.10	10.61	1.50
F	10	9.74	10.09	0.36
M	11	8.94	10.36	1.42
M	12	9.05	10.98	1.93
M	13	9.97	12.79	2.82
M	16	8.53	12.31	3.78
M	14	10.62	13.93	3.31
M	15	10.15	11.36	1.21
M	18	7.95	7.04*	-0.92*
M	17	10.82	13.08	2.26

All	**Mean**	8.89	10.48	1.58
	SD	1.23	2.05	1.47
	T test		0.0003	
Males	**Mean**	9.50	11.48	1.98
	SD	1.04	2.15	1.47
	T test		0.007	
Females	**Mean**	8.41	9.67	1.27
	SD	1.19	1.65	1.48
	T test		0.02	

Table 11. Shows the isokinetic knee extension torque at 60°/sec for all volunteers test by test. The summary panels show mean and standard deviations for all volunteers of body weight, for male and female volunteers separately. The t test cells show the results of tests between the initial value at the first test (T1) and subsequent tests.
* Indicates values which are less than the initial T1 value.

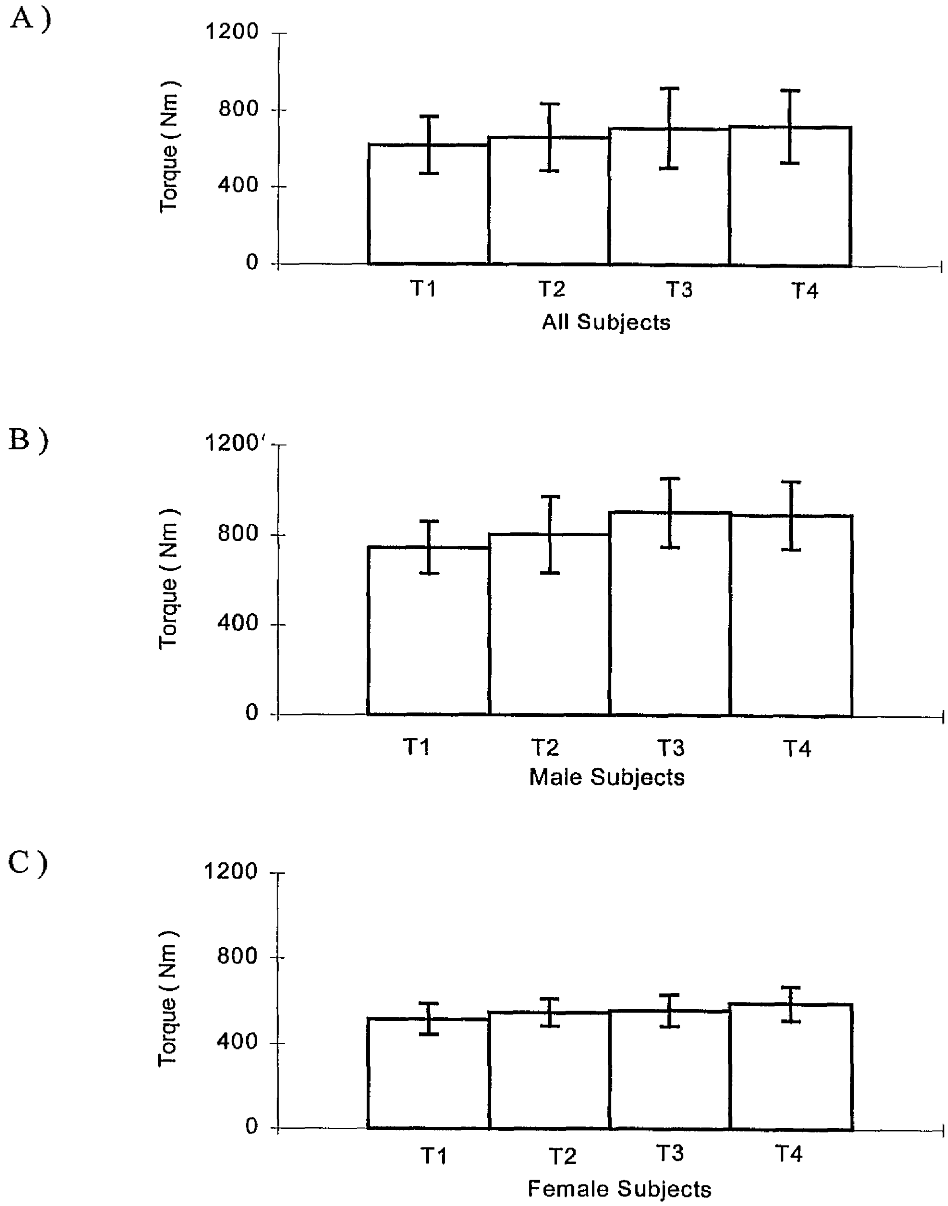


Figure 14. Mean and standard deviations of isokinetic knee extension torque at 60°/sec before and after training for A) all volunteers, B) male volunteers and C) female volunteers, in each figure the mean values for the initial test are shown on the left and the final test on the right. The torque increases between T1 and T4 are significant when tested with paired T tests, A ($P < 0.0001$). B ($P < 0.01$). C ($P < 0.01$).

A)
B)
C)

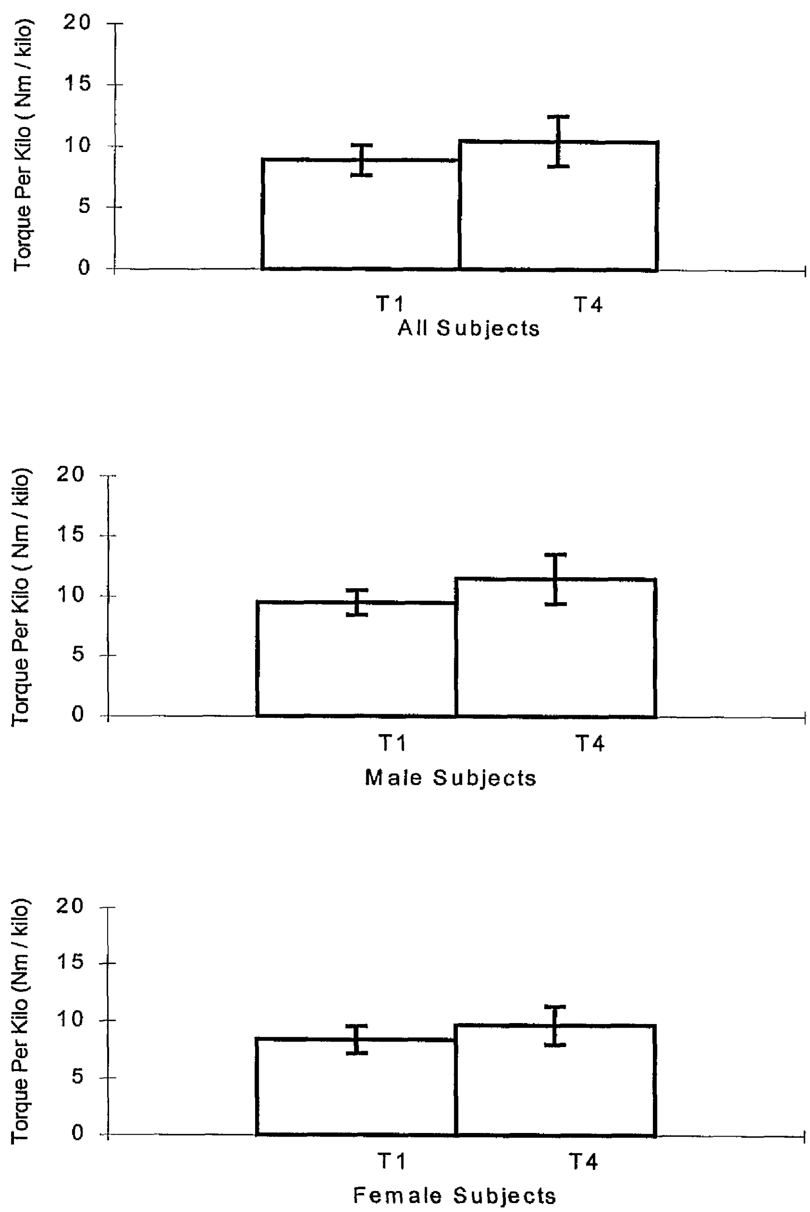


Figure 15. Mean and standard deviations of isokinetic knee extension torque at 60°/sec before and after training for A) all volunteers, B) male volunteers and C) female volunteers. The torque is normalised and expressed are torque per kilo body weight. The initial test values are on the left. The final values are on the right. The torque increases are significant when tested with paired T tests, A ($P < 0.0001$). B ($P < 0.001$). C ($P < 0.01$).

		1(Nm)	T2(Nm)	T3(Nm)	T4(Nm)	T4-T1(Nm)
F	3	287	259*	418	429	142
F	1	367	491	489	501	134
F	9	390	342*	441	436	46
F	2	401	467	466	454	53
F	7	415	454	467	486	71
F	4	455	515	403*	560	105
F	8	476	499	472*	466*	-10*
F	5	480	499	433*	562	82
F	10	523	602	598	563	40
F	6	540	507*	534*	614	74
M	12	420	556	692	664	244
M	11	556	574	623	642	86
M	18	601	695	704	648	47
M	14	608	747	777	893	285
M	13	618	755	793	794	176
M	16	675	903	962	1006	331
M	15	736	698*	772	842	106
M	17	905	961	1031	1013	108

All	**Mean**	525.2	584.7	615.3	642.9	117.8
	SD	149.8	180.6	191.6	190.2	89.8
	T test		0.003	0.001	0.001	
Males	**Mean**	639.9	736.1	794.3	812.8	172.9
	SD	141.0	141.8	137.8	152.8	103.3
	T test		0.013	0.002	0.002	
Females	**Mean**	433.4	463.5	472.1	507.1	73.7
	SD	76.7	96.4	58.0	63.7	45.6
	T test		0.117	0.089	0.0006	

Table 12. Shows the isokinetic knee extension torques at 180°/sec for all volunteers test by test. The summary panels show mean and standard deviations for all volunteers, for male and female volunteers separately. The t test cells show the results of tests between the initial value at the first test (T1) and subsequent tests.

* Indicates values which are less than the initial T1 value.

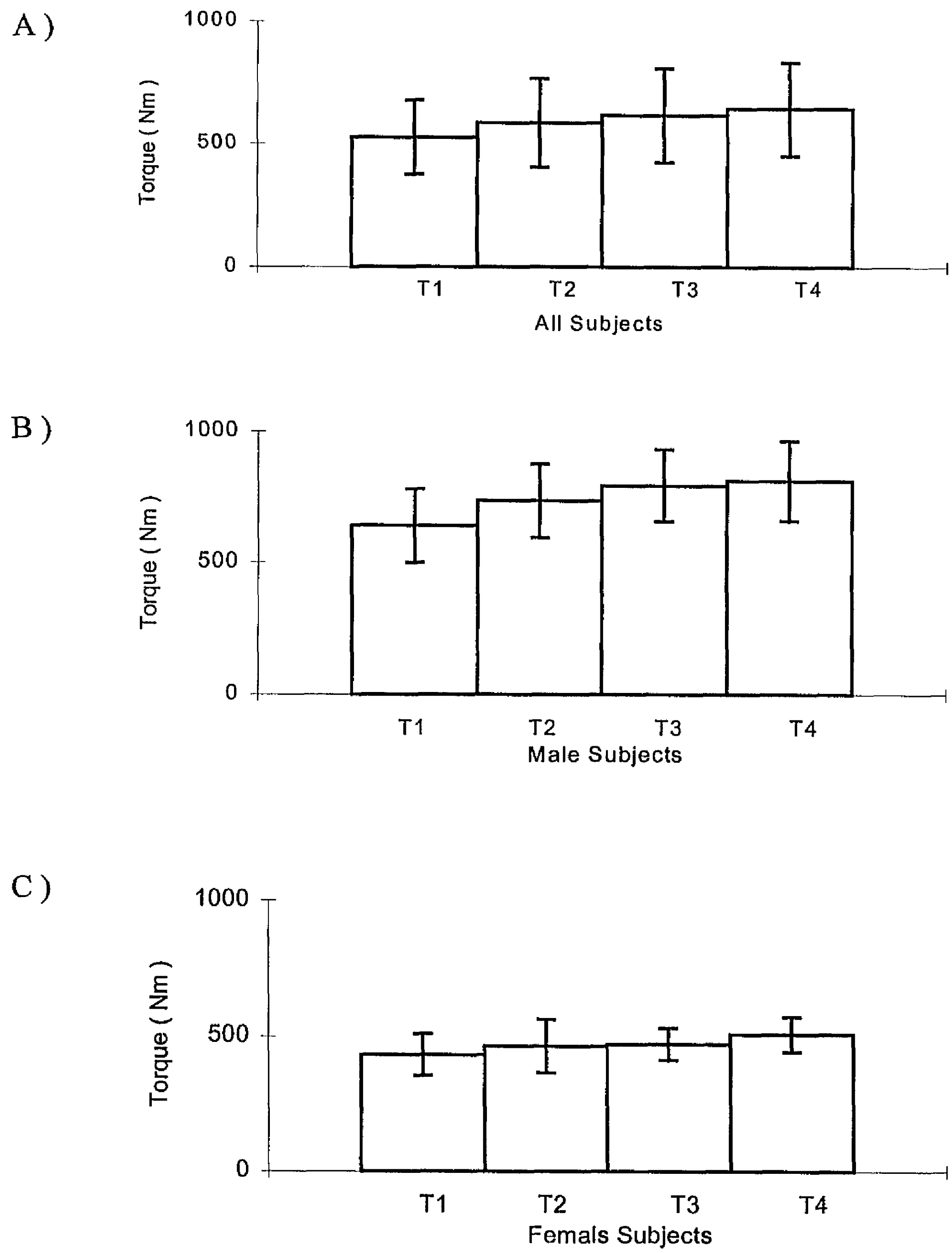


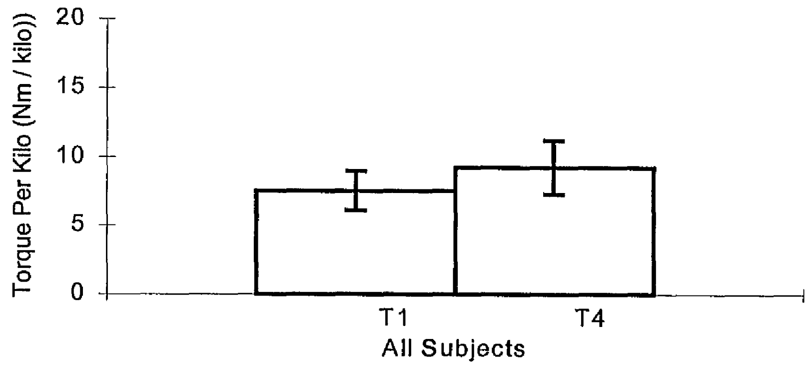
Figure 16. Mean and standard deviations of isokinetic knee extension torque at 180°/sec before and after training for A) all volunteers, B) male volunteers and C) female volunteers. The mean values (±SD) for the initial test are shown on the left and the final test on the right. The torque increases between T1 and T4 are significant when tested with paired T tests, A ($P < 0.00001$). B ($P < 0.001$). C ($P < 0.0001$).

		T1(Nm/kg)	T4(Nm/kg)	T4-T1(Nm/kg)
F	3	5.04	7.53	2.49
F	1	6.73	9.19	2.46
F	9	5.78	6.46	0.68
F	2	7.23	8.18	0.95
F	7	6.42	7.52	1.10
F	4	7.70	9.48	1.78
F	8	7.23	7.08*	-0.15*
F	5	7.80	9.14	1.33
F	10	7.69	8.28	0.59
F	6	8.75	9.95	1.20
M	12	6.13	9.69	3.56
M	11	8.32	9.61	1.29
M	18	5.56	6.00	0.44
M	14	8.56	12.58	4.01
M	13	9.00	11.56	2.56
M	16	8.07	12.03	3.96
M	15	9.10	10.41	1.31
M	17	10.65	11.92	1.27
All	**Mean**	7.54	9.26	1.71
	SD	1.44	1.95	1.21
	T test		0.00001	
Males	**Mean**	8.17	10.47	2.30
	SD	1.64	2.12	1.41
	T test		0.002	
Females	**Mean**	7.04	8.28	1.24
	SD	1.08	1.14	0.82
	T test		0.001	

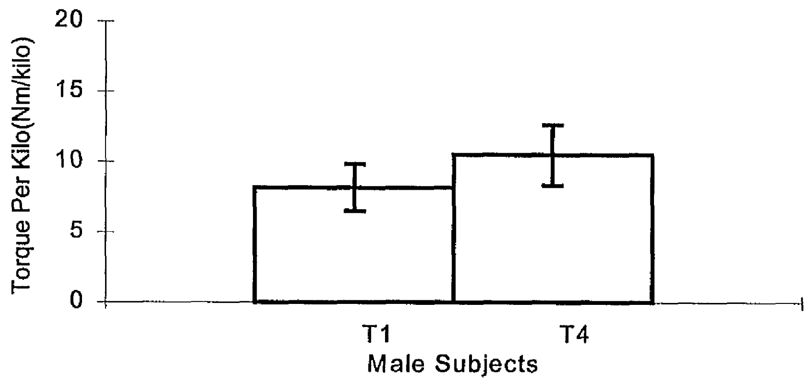
Table 13. Shows the isokinetic knee extension torque at 180°/sec for all volunteers test by test. The summary panels show mean and standard deviations for all volunteers of body weight, for male and female volunteers separately. The t test cells show the results of tests between the initial value at the first test (T1) and subsequent tests.

* Indicates values which are less than the initial T1 value.

A)



B)



C)

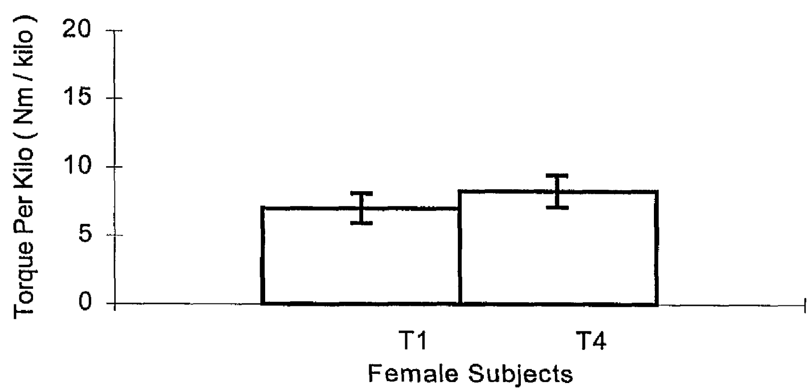


Figure 17. Mean and standard deviations of isokinetic knee extension torque at 180°/sec before and after training for A) all volunteers, B) male volunteers and C) female volunteers. The torques are normalised and expressed are torque per kilo body weight. The torque increases are significant when tested with paired T tests, A ($P < 0.00001$). B ($P < 0.002$). C ($P < 0.001$).

Velocity recordings

Recordings of the maximum knee and ankle joint velocities during leg extension were also made. These data are shown in Tables 14 and 15.

The first test was completed before training began. The range of maximum knee velocity was 134-346 degrees/sec. The mean for male volunteers was 247.4 $\pm$ 56.8 degrees/sec. The female volunteers had a mean velocity of 200.1 $\pm$ 33.9 degrees/sec. The difference between males and females was not significant when tested with a heteroscedastic T test ($P = 0.126$). When the volunteers returned for testing after two weeks training the maximum torque was measured. These values are shown in column T2 in table 14. The velocity had increased in all but two volunteers (10) and (15). This overall increase was significant ($P < 0.001$) when tested with a paired T test. The velocity continued to increase in the third and fourth test sessions, i.e. after 4 and 6 weeks of training. These values are shown in columns T3 and T4.The column T4-T1 showed the values of mean velocity increase in all volunteers 77.4 $\pm$ 74.7 degrees/sec. A paired T test showed the increase was significant ($P < 0.0003$). When the analysis was repeated for the male volunteers, the mean velocity increase was 57.5 $\pm$ 82.7 degrees/sec. This increase was significant ($P < 0.05$). The increase in velocity for the female volunteers was 91.3 $\pm$ 69.4 degrees/sec. This also was significant ($P < 0.003$). These results are shown graphically in Figure 18.

In addition, in both the initial and final tests the females were significantly faster than the males. However, in the velocity tests at knee joint both groups increased their performance by approximately 46% (female) and 23% (male).

Similar experiments were repeated on the same volunteers to examine the range of ankle joint velocities. These data are shown in Table 15. At the first test the range of maximum velocity was between 112 - 296 degrees/sec. The mean for male volunteers was 231 $\pm$ 51.3 degrees/sec. The female volunteers had a mean velocity of 165.8 $\pm$ 46.9 degrees/sec. The difference between female and male was significant, when tested with a heteroscedastic T test ($P = 0.013$).

When the volunteers returned for testing after two weeks training the maximum ankle velocity was measured. These values are shown in column T2 in table 15. The velocity had increased in nine volunteers. This overall increase was not significant ($P < 0.7$) when tested with a paired T test. The velocity continued to increase in the third and fourth test. These values are shown in columns T3 and T4 of table 15.

The column T4-T1 showed the values of mean velocity increase in all volunteers 16.3 $\pm$ 59.3 degrees/sec. A paired T test showed the increase was not significant ($P < 0.3$). When the analysis was repeated for the male volunteers, the mean velocity increase was -13.1 $\pm$ 49.7 degrees/sec. This change was not significant ($P < 0.5$). The increase in velocity for the female volunteers was 39.9 $\pm$ 57.8 degrees/sec. This was not significant at $P<0.05$ ($P = 0.06$). These results are shown graphically in Figure 19.

In addition, in the initial and final tests, the females were significantly faster than the males. However, the velocity of the ankle extension in the group increased performance by approximately 24% but the velocities of the male group decreased by approximately -6%.

		T1°/s	T2 °/s	T3 °/s	T4 °/s	T4-T1 °/s
F	3	134	175	206	232	98
F	4	153	229	184	213	60
F	1	168	171	191	251	83
F	9	187	194	203	200	13
F	7	189	294	295	248	59
F	10	207	182*	213	257	50
F	2	209	231	262	317	108
F	6	229	279	317	362	133
F	5	233	253	314	270	37
F	8	260	266	312	519	259
M	12	166	229	264	277	111
M	18	171	177	282	255	84
M	15	223	222*	302	194*	-29.5*
M	13	225	286	273	283	58
M	11	229	356	349	394	165
M	14	242	352	358	400	158
M	16	296	313	224*	270*	-26*
M	17	346	356	242*	339*	-7*

All	**Mean**	219.6	258.2	269.7	297.0	77.4
	SD	49.3	61.9	53.7	84.0	74.7
	T test		0.001	0.003	0.0003	
Males	**Mean**	247.4	294.6	290.0	304.9	57.5
	SD	56.8	71.1	50.4	76.1	82.7
	T test		0.026	0.157	0.055	
Females	**Mean**	200.1	232.8	255.5	291.4	91.3
	SD	33.9	41.3	53.7	92.7	69.4
	T test		0.033	0.0008	0.003	

Table 14. Shows the velocity of the knee for all volunteers test by test. The summary panels show mean and standard deviations for all volunteers, for male and female volunteers separately. The t test cells show the results of tests between the initial value at the first test (T1) and subsequent tests.
* Indicates values which are less than the initial T1 value.

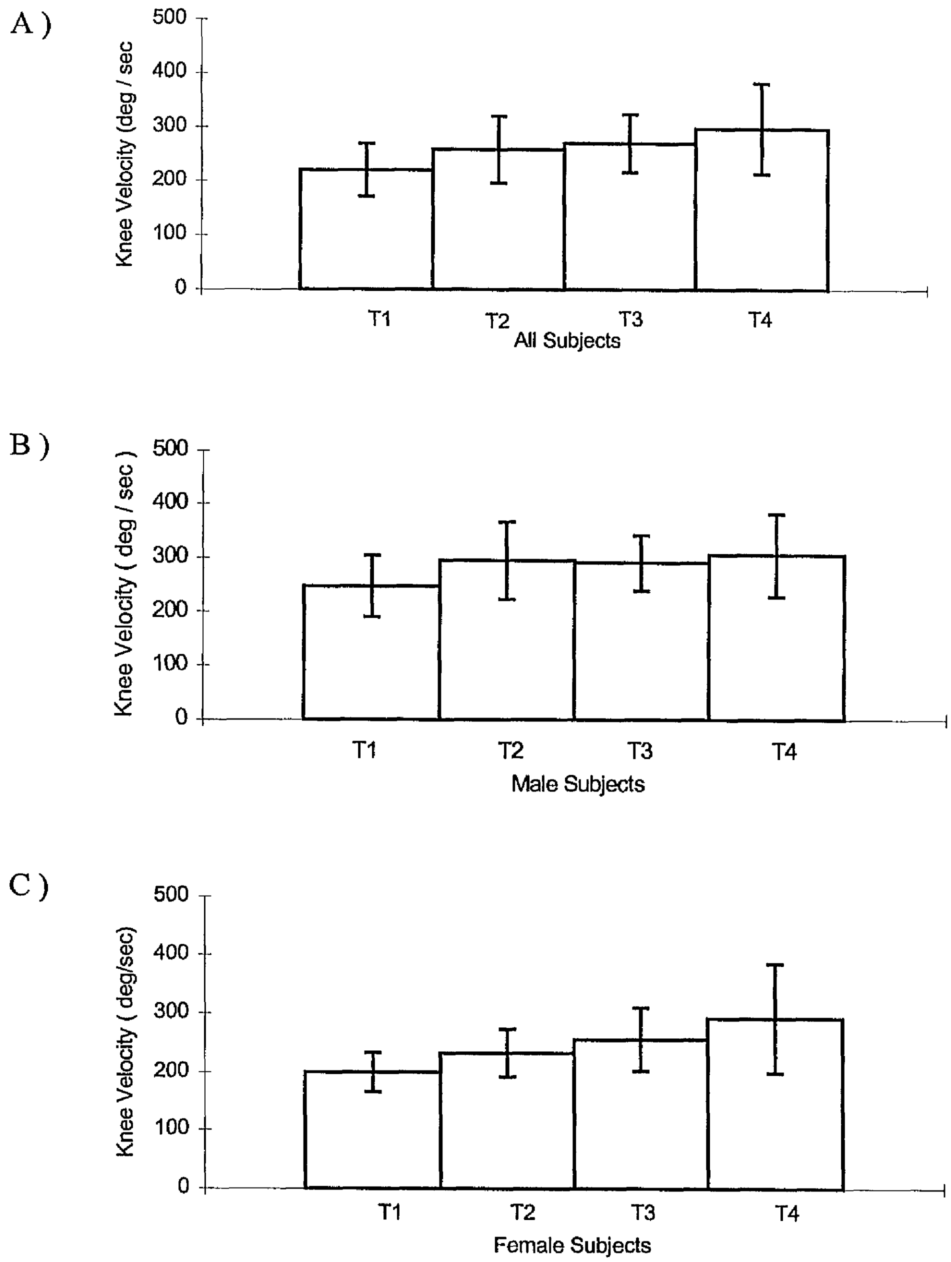


Figure 18. Mean and standard deviations of knee extension velocity before and after training for A) all volunteers, B) male volunteers and C) female volunteers, figures in each the mean values for the initial test are shown on the left and the final test on the right. The velocity increases are significant when tested with paired T tests, A ($P < 0.0002$). B ($P < 0.05$). C ($P < 0.002$).

Sex	Volunteer	T1 °/s	T2 °/s	T3 °/s	T4 °/s	T4-T1 °/s
F	7	112	135	145	181	69
F	2	122	200	120*	126	4
F	9	123	175	173	134	11
F	5	140	203	184	229	89
F	3	160	183	175	181	21
F	6	160	153*	181	183	23
F	1	184	120*	187	168*	-16*
F	10	192	259	286	308	116
F	8	197	184*	338	325	128
F	4	268	209*	190*	222*	-46*
M	11	160	139*	158*	181	21
M	12	166	213	143*	178	12
M	17	200	238	273	264	64
M	18	240	225*	187*	229*	-11*
M	14	242	235*	291	244	2
M	15	269	303	251*	235*	-34*
M	13	279	169*	216*	194*	-85*
M	16	296	262*	276*	222*	-74*

All	**Mean**	195.0	200.3	209.7	211.3	16.3
	SD	58.1	48.6	61.3	52.9	59.3
	T test		0.667	0.280	0.259	
Males	**Mean**	231.5	223.0	224.4	218.4	-13.1
	SD	51.3	51.2	56.9	31.1	49.7
	T test		0.652	0.680	0.479	
Females	**Mean**	165.8	182.1	197.9	205.7	39.9
	SD	46.9	40.0	65.0	66.8	57.8
	T test		0.339	0.116	0.057	

Table 15. Shows the velocity of the ankle for all volunteers test by test. The summary panels show mean and standard deviations for all volunteers, for male and female volunteers separately. The t test cells show the results of tests between the initial value at the first test (T1) and subsequent tests.
* Indicates values which are less than the initial T1 value.

Joint accelerations

The maximum accelerations of the knee joint and ankle joint were also calculated. These data are shown in Tables 16 and 17. At the first test, the range of maximum acceleration was between 226-610 degrees/sec/sec. The mean for male volunteers was 456.3 ± 105.5 degrees/sec/sec. The female volunteers had a mean acceleration of 408.3 ± 97.5 degrees/sec/sec. The difference between females and males was significant, when tested with a heteroscedastic T test.

When the volunteers returned for testing after two weeks training the maximum acceleration was measured. These values are shown in column T2 in table 15. The acceleration had increased in 13 volunteers. This overall increase was significant ($P < 0.04$) when tested with a paired T test. The acceleration continued to increase in the third and fourth test sessions, i.e. after 4 and 6 weeks of training. These values are shown in columns T3 and T4 of table 16.

	Volunteer	T1 °/s/s	T2 °/s/s	T3 °/s/s	T4 °/s/s	T4-T1 °/s/s
F	3	226	291	400	418	192
F	4	314	457	382	440	126
F	9	335	353	369	364	29
F	7	347	554	531	679	332
F	1	348	277*	286*	357	9
F	10	389	321*	409	483	94
F	2	404	462	540	706	302
F	6	440	558	629	725	285
F	8	467	423*	824	972	505
F	5	631	514*	636	535*	-96*
M	12	317	330	519	538	221
M	18	322	361	514	582	260
M	11	440	640	691	766	326
M	13	449	522	540	561	112
M	15	455	417*	651	423*	-32*
M	14	473	699	655	808	335
M	16	584	639	453*	545	-39*
M	17	610	642	452*	681	71*

All	**Mean**	430.9	480.5	534.2	597.9	167.1
	SD	101.2	129.2	136.5	167.2	168.3
	T test		0.046	0.004	0.0004	
Males	**Mean**	456.3	531.3	559.4	613.0	156.8
	SD	105.5	144.7	93.9	128.8	150.5
	T test		0.053	0.110	0.022	
Females	**Mean**	408.3	435.4	511.8	584.6	176.2
	CI					118.6
	T test		0.380	0.083	0.028	

Table 16. Shows the acceleration of the knee joint for all volunteers test by test. The summary panels show mean and standard deviations for all volunteers, for male and female volunteers separately. The t test cells show the results of tests between the initial value at the first test (T1) and subsequent tests.
* Indicates accelerations which are less than the initial T1 value.

A)

B)

C)

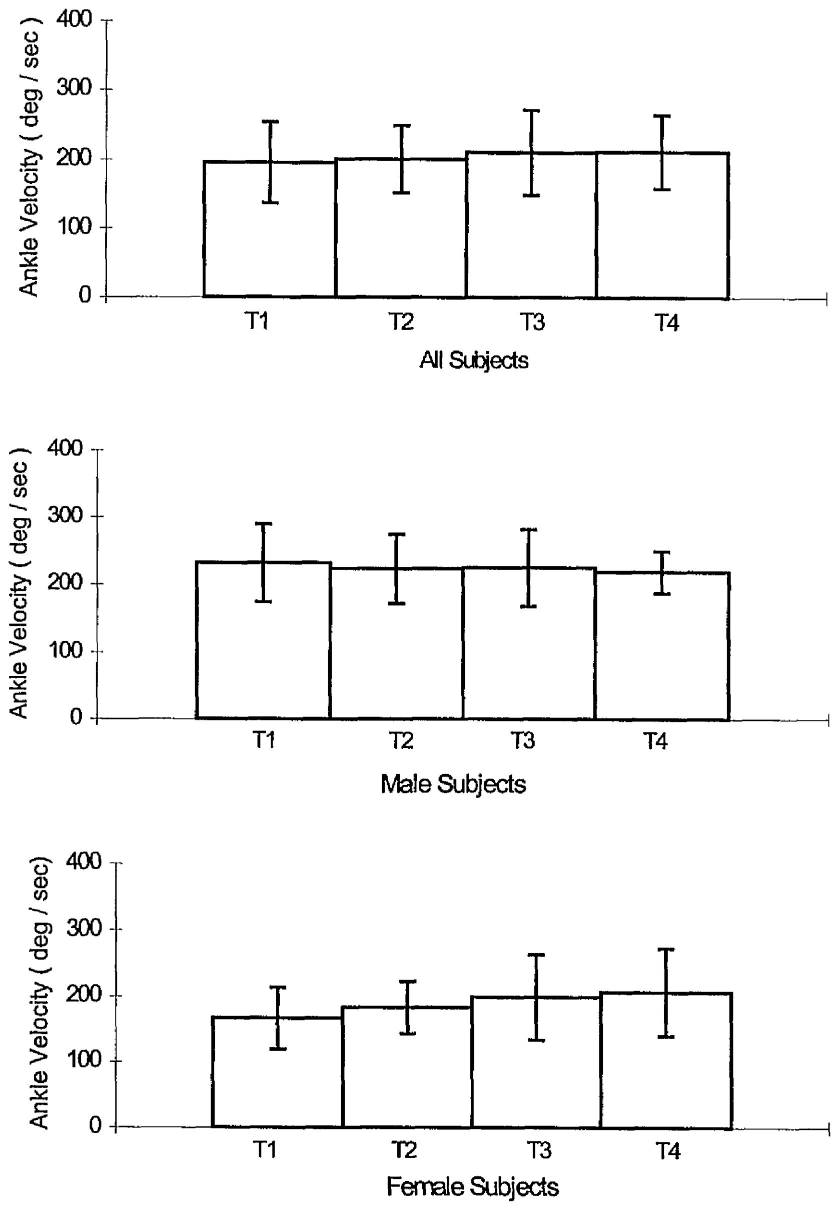


Figure 19. Mean and standard deviations of ankle velocity before and after training for: A) all volunteers, B) male volunteers and C) female volunteers. The changes in A and B are not significant A ($P < 0.2$). B ($P < 0.4$). C shows a significant increase when tested with paired T tests ($P < 0.05$).

The column T4-T1 in table 16 shows the values of mean acceleration increase in all volunteers by 167.1 ± 168.3 degrees/sec/sec. A paired T test showed the increase was significant ($P < 0.0004$). When the analysis was repeated for the male volunteers, the mean acceleration increase was 156.8 ± 150.5 degrees/sec/sec. This increase was significant ($P < 0.02$). The increase in acceleration for the female volunteers was 176.2 ± 191.4 degrees/sec/sec. This also was significant ($P < 0.03$). These results are shown graphically in Figure 20.

In addition, in the initial and final tests the females were significantly faster than the males. The increase in their performance was approximately 43% (female) and 34% (male).

Similar experiments were repeated on the same volunteers with the ankle joint. These data are shown in table 17. At the second test the range of maximum acceleration was between 193 - 564 degrees/sec/sec. The mean for male volunteers was 468.9 ± 91.7 degrees/sec/sec. The female volunteers had a mean velocity of 310.8 ± 119.5 degrees/sec/sec. The difference between females and males was significant, when tested with a heteroscedastic T test.

When the volunteers returned for testing after two weeks training the maximum ankle acceleration was measured again. These values are shown in column T2 in table 17. The acceleration had increased in 13 volunteers. This overall increase was not significant ($P < 0.2$) when tested with a paired T test.

The values recorded at the third and fourth test sessions are shown in columns T3 and T4. The column T4-T1 in table 17 shows the values of mean acceleration increase in all volunteers to be 75.2 ± 186.1 degrees/sec/sec. A paired T test showed the increase not significant ($P < 0.06$). When the analysis was repeated for the male volunteers, the mean acceleration increase was 36.9 ± 236.4 degrees/sec/sec. This increase was not significant ($P < 0.6$). The increase in acceleration for the female volunteers was 102.1 ± 149.5 degrees/sec/sec. This also was significant ($P < 0.04$). These results are shown graphically in Figure 21.

In addition, in the initial and final tests the females were significantly faster than the males. The ankle velocity of both groups increased, 33% (female) and 8% (male).

	Volunteer	T1 °/s/s	T2 °/s/s	T3 °/s/s	T4 °/s/s	T4-T1 °/s/s)
F	2	193	382	247	499	306
F	6	204	314	369	374	170
F	7	229	278	321	540	311
F	9	244	333	276	268	24
F	5	260	334	313	392	132
F	3	283	353	338	340	57
F	1	312	197*	260*	274*	-38
F	8	325	343	400	542	217
F	10	352	449	558	603	251
F	4	626	443*	363*	430*	-196*
M	11	273	249*	314	366	93
M	12	348	396	321*	150*	-198*
M	14	370	465	525	488	118
M	17	405	597	650	839	434
M	18	506	423*	453*	748	242
M	16	538	615	548	423*	-115*
M	13	551	402*	431*	382*	-169*
M	15	564	674	475*	510*	-54*

All	**Mean**	375.9	403.8	406.8	451.1	75.2
	SD	132.7	129.8	112.4	172.0	186.1
	T test		0.164	0.284	0.064	
Males	**Mean**	468.9	510.3	486.1	505.7	36.9
	SD	91.7	115.3	103.1	230.5	236.4
	T test		0.427	0.660	0.590	
Females	**Mean**	310.8	329.3	351.2	412.9	102.1
	SD	119.5	78.1	84.0	115.0	149.5
	T test		0.283	0.331	0.040	

Table 17. Shows the acceleration of the ankle joint for all volunteers test by test. The summary panels show mean and standard deviations for all volunteers, for male and female volunteers separately. The t test cells show the results of tests between the initial value at the first test (T1) and subsequent tests.
(* indicates accelerations less than the initial T1 value.)

A)

B)

C)

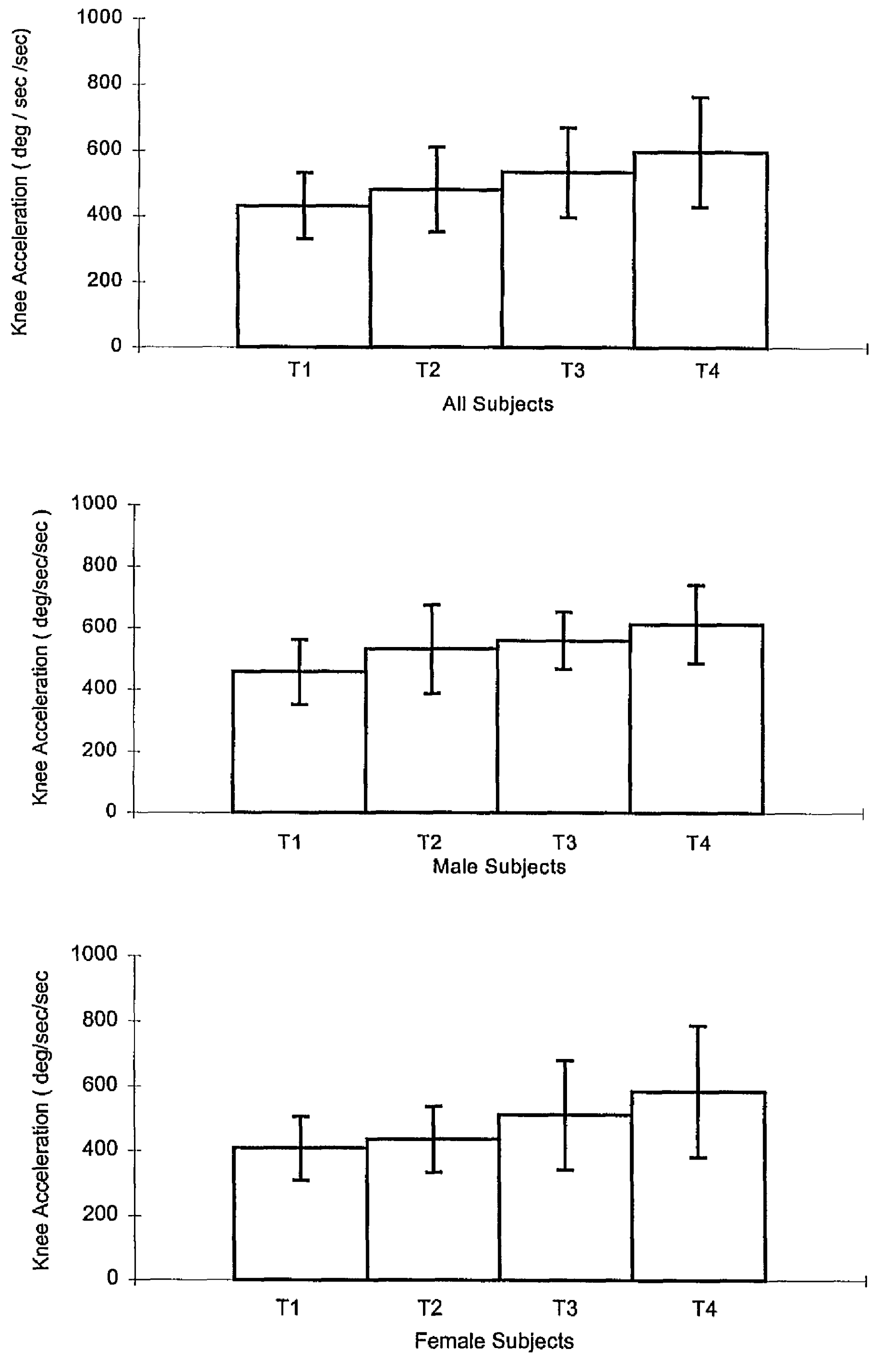


Figure 20 Mean and standard deviations of accelerations recorded at knee joint before and after training for A) all volunteers, B) male volunteers and C) female volunteers, figures in the mean values for the initial test are shown on the left and the final test on the right. The acceleration increases are significant when tested with paired T tests, A ($P < 0.0001$). B ($P < 0.02$). C ($P < 0.02$).

A)

B)

C)

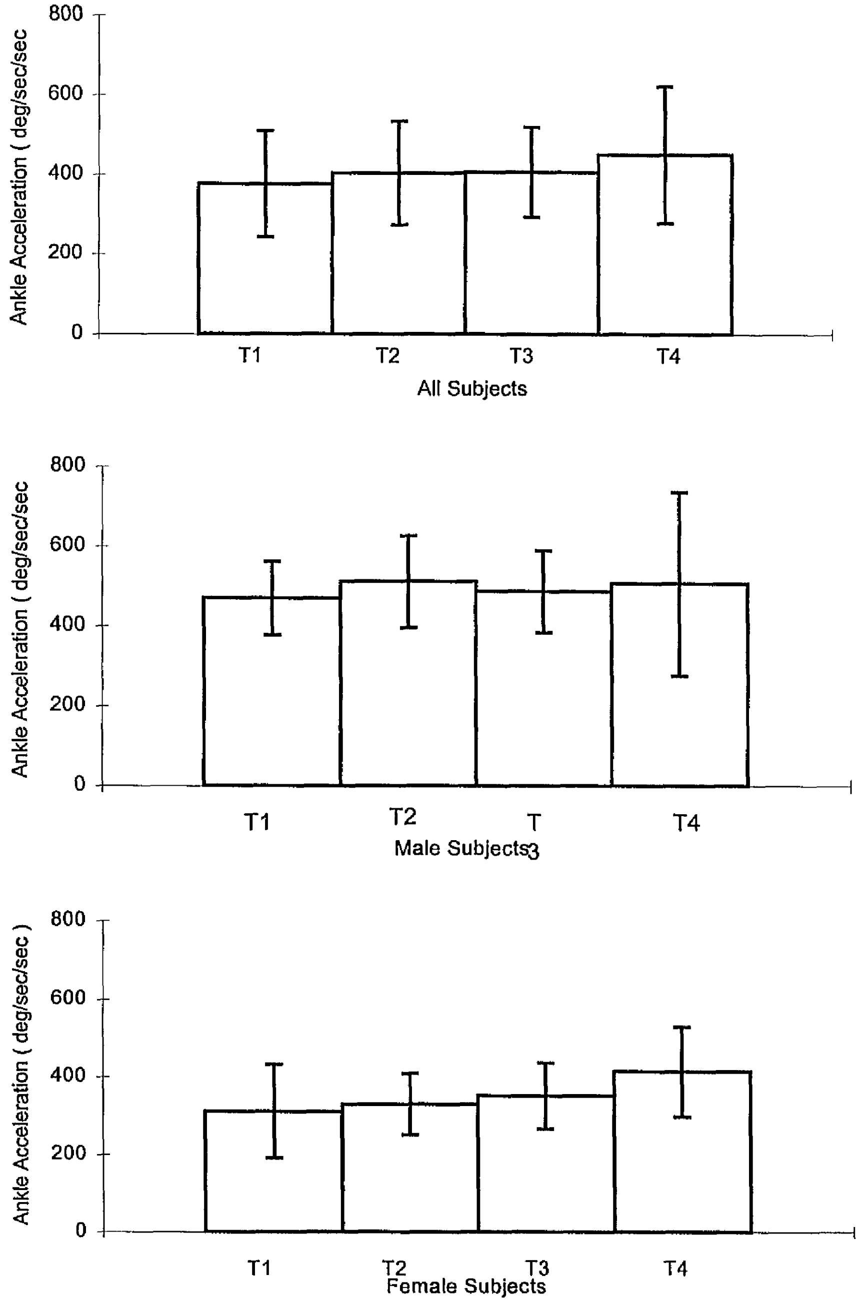


Figure 21. Mean and standard deviations of accelerations at ankle joint before and after training for A) all volunteers, B) male volunteers and C) female volunteers, figures in each the mean values for the initial test are shown on the left and the final test on the right. The acceleration changes are not significant for A and B , but acceleration increases for C is significant when tested with paired T tests, A ($P < 0.06$). B ($P < 0.5$). C ($P < 0.03$).

Second series of experiments. Isometric recording

The details of the volunteers who completed the second series of experiment are shown in Table 3 in the methods section. Significant differences in body height and body weight between males and females are shown in table 18.

		Age (year)	Height (cm)	Weight (kg)
All	**Range**	19 - 23	157 - 185	54 - 107
	Mean	20.56	172.7	71.9
	SD	1	8.5	13.7
Males	**Range**	19 - 23	166 - 185	56 - 107
	Mean	20.7	177.5	78.6
	SD	1.1	6.4	12.6
Females	**Range**	19 -21	157 - 169	54 - 82
	Mean	20.3	165.4	61.9
	SD	0.7	5.6	8.1
T test F vs. M		0.117	0.0001	0.0002

Table 18. Shows a summary of physical characteristics of the volunteers who participated in the second series of experiments.

In these experiments the maximum of right knee extension torque was measured at 110°, 80°, 50° and 10° of knee flexion. These data are shown in tables 19 and 20.

At 110° a range of torques between 491-1149 Nm was measured. The mean value for male volunteers was 846.9 $\pm$ 166.2 Nm. The female volunteers had a mean torque of 593.7 $\pm$ 70 Nm. Thus the males were significantly stronger than females when tested with a heteroscedastic T test. ($P < 0.00001$).

The volunteers were stronger when tested at 80°. This test produced a range of torques between 723-1274 Nm. The mean value for male volunteers were 1125.4 $\pm$ 172.9 Nm. The female volunteers had a mean torque of 739.5 $\pm$ 64.5 Nm. The difference was significant ($P < 0.0001$).

The torque fell at 50° where the range of torques was between 365 - 896 Nm. The mean value for male volunteers was 736.2 $\pm$ 152.5 Nm. The female volunteers had a mean torque of 531 $\pm$ 120.4 Nm. Again the difference was significant ($P <0.0001$). The lowest torques were recorded at 10°. The range of values lay between 77-281 Nm. The mean value for male volunteers was 240.7 $\pm$ 63 Nm. These data are illustrated in figure 22.

The knee extension torque was divided by the body weight of each volunteer to calculate torque/kilo. These data are shown in Table 20. Even when the data has been corrected for the effects of body size, the males are significantly stronger than the females these data are illustrated in figure 23.

Volunteer	Sex	110°	80°	50°	10°
		Nm	Nm	Nm	Nm
26	F	491	723	365	77
27	F	533	719	394	84
28	F	557	632	419	119
29	F	558	688	521	177
30	F	571	801	644	224
31	F	580	669	453	116
32	F	592	769	717	225
33	F	655	756	578	185
34	F	690	823	651	235
35	F	710	815	568	185
36	M	586	755	375	124
37	M	599	746	507	177
38	M	671	1099	771	317
39	M	740	1317	776	231
40	M	749	1019	637	333
41	M	790	1126	787	236
42	M	813	1227	745	248
43	M	834	1230	853	227
44	M	860	1136	930	270
45	M	907	1095	837	328
46	M	945	1266	804	262
47	M	986	1120	643	146
48	M	989	1237	857	249
49	M	1085	1234	625	181
50	M	1149	1274	896	281
All	**Mean**	745.6	971.04	654.12	209.48
	SD	184.3	237.1	171.8	71.8
	T test		0.0001	0.0001	0.0001
Males	**Mean**	846.87	1125.40	736.20	240.67
	SD	166.2	172.9	152.5	63.0
Females	**Mean**	593.7	739.5	531	162.7
	SD	70.0	64.5	120.4	59.3
	T test	0.0001	0.0001	0.001	0.003

Table 19. Shows the isometric extension torque with the knee at 110°, 80°, 50°and 10° of flexion for all volunteers test by test. The summary panels show mean and standard deviations for all volunteers, for male and female volunteers separately. The t test cells show the results of tests between the initial value at the first test (T1) and subsequent tests, i.e. T1vs T2, T1 vs. T3 and T1 vs. T4.

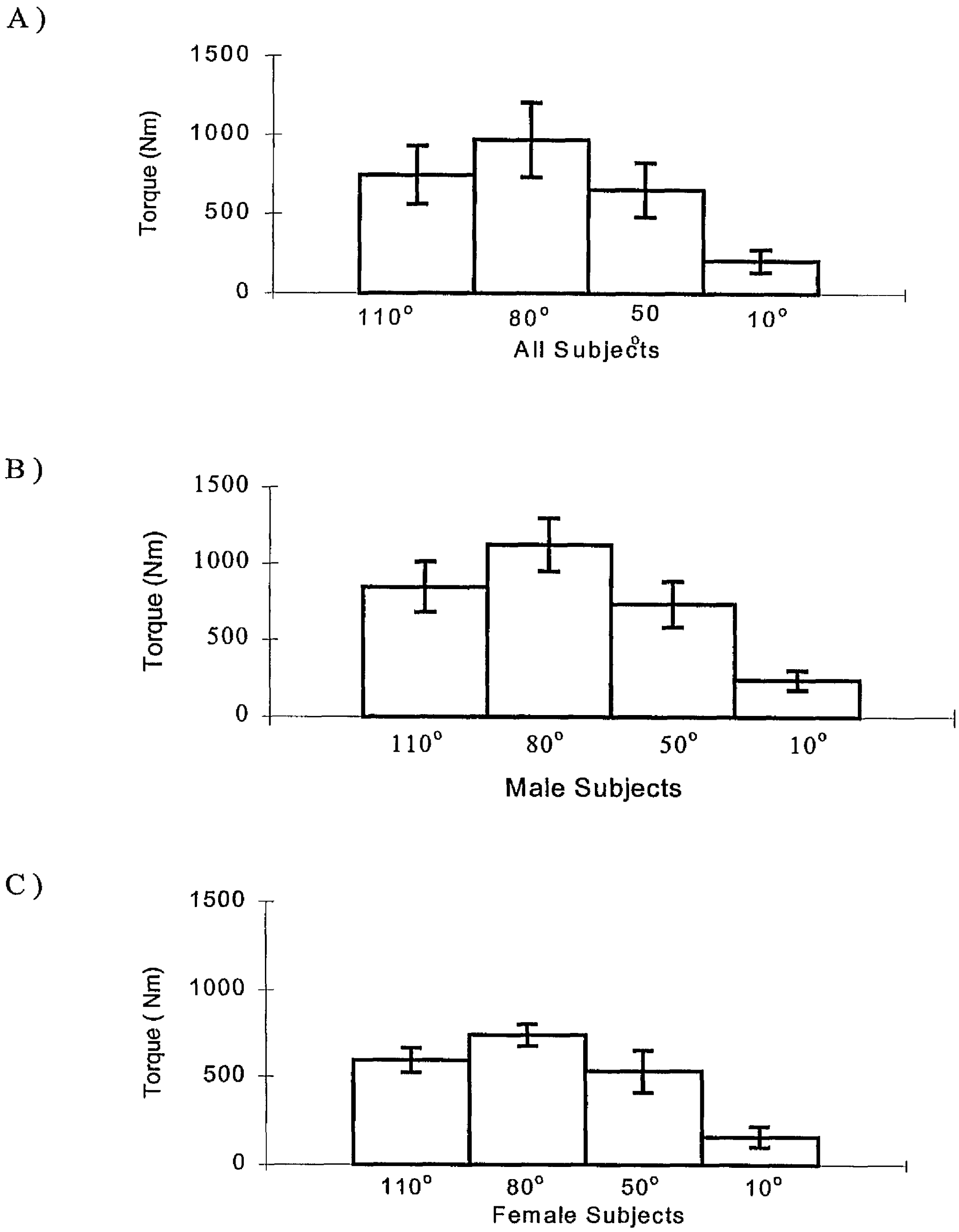
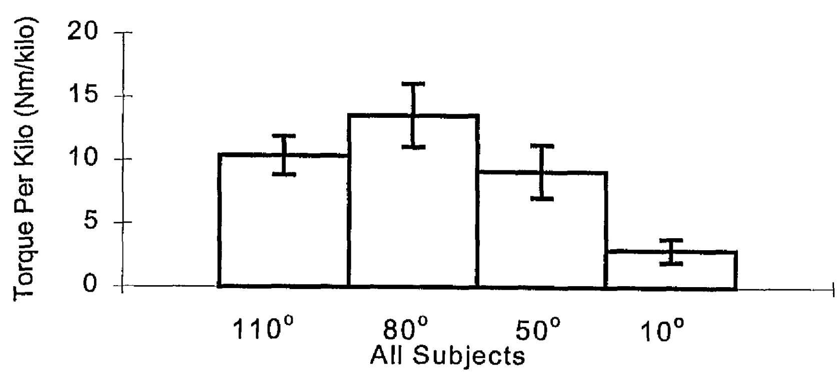


Figure 22. Mean and standard deviations of isometric knee extension torque at 110°, 80°, 50° and 10° of knee flexion for A) all volunteers, B) male volunteers and C) female volunteers.

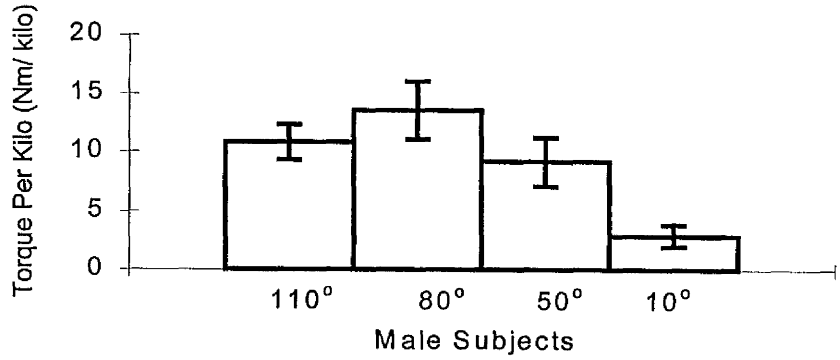
Volunteer	Sex	110°/Nm/kg	80°/Nm/kg	50°/Nm/kg	10°/Nm/kg
26	F	7.94	11.70	5.91	1.25
27	F	9.13	12.31	6.75	1.44
28	F	10.04	11.39	7.55	2.14
29	F	9.19	11.33	8.58	2.92
30	F	8.72	12.23	9.83	3.42
31	F	9.35	10.79	7.31	1.87
32	F	9.29	12.07	11.26	3.53
33	F	12.20	14.08	10.76	3.45
34	F	12.41	14.80	11.71	4.23
35	F	8.64	9.91	6.91	2.25
36	M	10.46	13.48	6.70	2.21
37	M	7.63	9.50	6.46	2.25
38	M	10.17	16.65	11.68	4.80
39	M	9.34	16.63	9.80	2.92
40	M	9.36	12.74	7.96	4.16
41	M	10.84	15.45	10.80	3.24
42	M	12.57	18.96	11.51	3.83
43	M	12.14	17.90	12.42	3.30
44	M	10.70	14.13	11.57	3.36
45	M	10.31	12.44	9.51	3.73
46	M	13.13	17.58	11.17	3.64
47	M	11.15	12.67	7.27	1.65
48	M	11.53	14.42	9.99	2.90
49	M	12.00	13.65	6.91	2.00
50	M	10.74	11.91	8.37	2.63
All	**Mean**	10.36	13.55	9.15	2.92
	SD	1.5	2.5	2.1	0.9
	T test		0.001	0.001	0.001
Males	**Mean**	10.80	14.54	9.47	3.11
	SD	1.4	2.6	2.0	0.9
Females	**Mean**	9.69	12.06	8.66	2.65
	SD	1.5	1.5	2.1	1.0
	T test	0.038	0.003	0.173	0.126

Table 20. Shows the isometric knee extension torque expressed per kilo body weight with the knee at 110°, 80°, 50° and 10° of flexion for all volunteers at the initial and final tests. The summary panels show mean and standard deviations for all volunteers and for male and female volunteers separately. The t test cells show the results of tests between initial value at the first test (T1) and subsequent tests, i.e. T1vs T2, T1 vs. T3 and T1 vs. T4.

A)



B)



C)

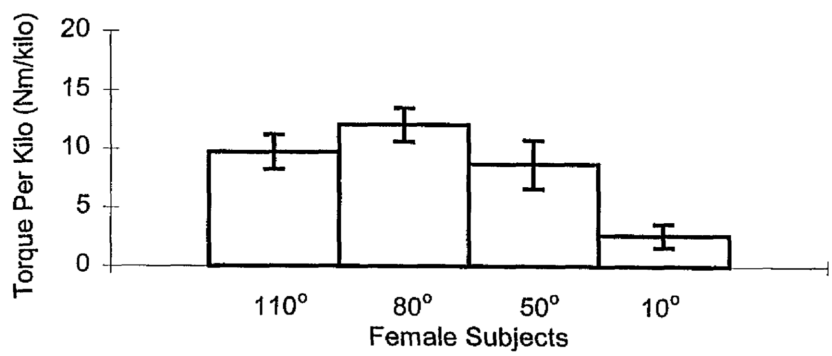


Figure 23. Mean and standard deviations of isometric knee extension torque with the knee at 110°, 80°, 50° and 10° of flexion for: A) all volunteers, B) male volunteers and C) female volunteers. The torque is normalised and expressed as torque per kilo body weight.

Velocity recording under different load conditions

Recordings of the velocity of knee extension were made as volunteers lifted a series of progressively greater loads. These data are shown in Table 21. The initial test was done with a load of 48 kg. The design of the leg press imposed this as a minimum load. Any reduction of this would have required redesign and reconstruction of the device beyond the scope of this project. The load will be relatively higher for smaller or weaker volunteers. However, this effect is probably small and does not change the result since no significant changes in velocity are observed until loads exceed 100kg. This can be seen in figure 24 and table 21. The range of maximum knee velocity under this load was between 169-379°/s. The female volunteers had a mean velocity of 288 + 41.6 ° /s and the mean for male volunteers was 269.8 + 49.7°/s. The difference was insignificant ($P < 0.16$) when tested with a heteroscedastic T test. The velocity shows variation between volunteers lifting the same load. However, for any one volunteer it can be seen that the trend is for the velocity to fall as the load increases. This is seen in the progressive decrease in mean velocity as the load increases. The greatest load lifted by the female volunteers was 208 kg, whilst most of the males were capable of greater lifts.

The comparison of velocities is difficult because above 128kg the number of volunteers lifting each load drops with each increase in load. In addition, each absolute load represents a different proportion of the maximum for each volunteer.

One surprising observation is that the minimum velocity for each volunteer is relatively high and shows relatively little variation despite much greater variation in maximum load, shown in figure 24.

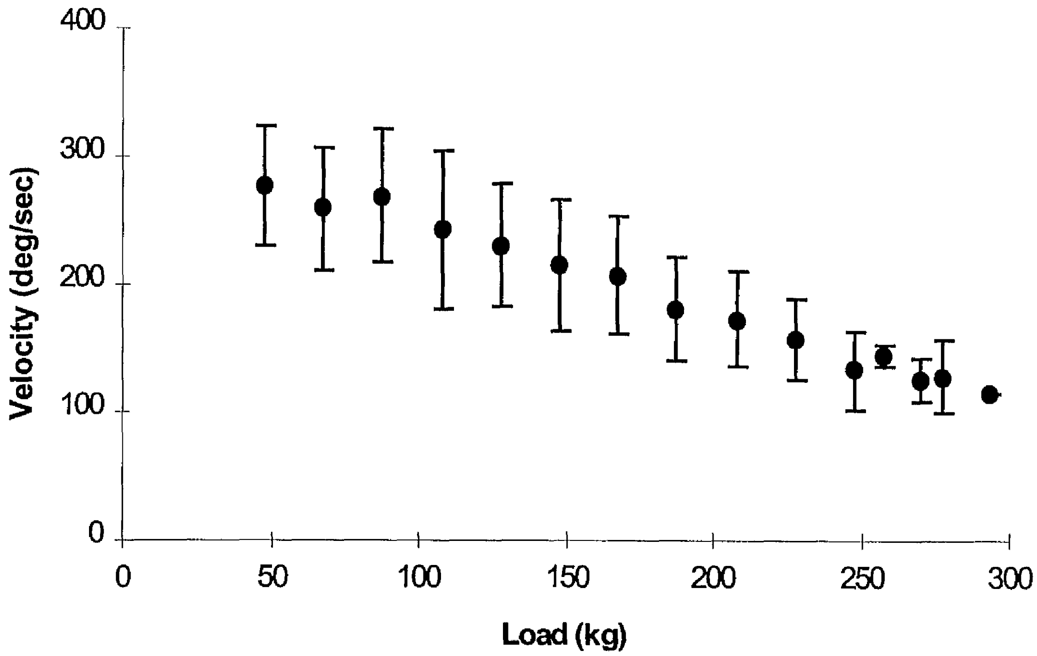


Figure 24. This shows the mean (± SD) velocity of knee extension in up to 25 volunteers as the load was increased.

Volunteer	Sex	48kg	68kg	88kg	108kg	128kg	148kg	168kg	188kg	208kg	228kg	238kg	248kg	258kg	270kg	278kg	293kg
1	F	222	265	218	190	192	178	149	118	125							
2	F	244	187	220	207	203	162	181									
3	F	244	224	229	217	239	244	181	200	158							
4	F	274	296	283	209	220	231	255	112								
5	F	282	333	292	308	260	244	194	127								
6	F	304	251	255	242	244	184										
7	F	314	255	229	181	126											
8	F	317	229	265	165												
9	F	336	321	405	379	260	265	200									
10	F	343	207	325	127	122	86										
11	M	169	171	194	196	222	183	213	196	181	121	92					
12	M	218	257	273	281	239	220	290	197	191	167	147	152	139	150	149	114
13	M	218	200	213	178	192	140	121									
14	M	229	213	194	202	196	177	166	165	168	158	147	136	125	108	114	114
15	M	247	235	226	226	229	220	209	200	197	171	161	153	110			
16	M	266	251	257	238	239	210	175	168	155	100						
17	M	270	227	255	251	231	190	174	174	155	143	97					
18	M	274	270	291	274	317	269	269	239	212	178						
19	M	279	260	231	210	209	209	222	204	166	149	103					
20	M	289	274	319	255	229	229	213	158	97							
21	M	292	255	257	226	220	191										
22	M	301	333	315	358	296	308	281	239	229	169	140					
23	M	304	307	308	317	307	255	239	152								
24	M	312	350	346	275	257	235	161									
25	M	379	305	321	327	283	301	255	238	216	220	174	151	117			

All	**Mean**	277.0	259	268.8	241.6	230.5	214.4	207.4	180.4	173.1	157.6	132.6	148	122.8	129	131.5	114
	SD	46.6	47.6	51.7	61.6	47.4	50.8	46.1	41.0	37.1	32.7	31.1	8.0	12.4	29.7	24.7	0.0
Males	**Mean**	269.8	260.5	266.7	254.3	244.4	222.5	213.4	194.2	178.8	157.6	132.6	148	122.8	129	131.5	114
	SD	49.7	48.9	48.8	51.6	39.3	46.1	50.1	31.8	36.9	32.7	31.1	8.0	12.4	29.7	24.7	0.0
Females	**Mean**	288	256.8	272.1	222.5	207.3	199.2	193.3	139.2	141.5							
	SD	41.6	48.0	58.4	72.9	52.7	58.8	35.0	41.0	23.3							

Table 21. Shows the maximum velocity of knee joint extension for all volunteers test by test. The summary panels show mean and standard deviations for all volunteers, for male and female volunteers separately.

DISCUSSION

Summary of Results

The first series of experiments, the training study, succeeded in producing significant gains in isometric and isokinetic strength of the volunteers. It also produced significant increases in knee extension velocity. As a result of a training programme lasting six weeks isometric force at 70 and 60 degrees increased by an average of 21% for all volunteers. These results are shown in tables 5 and 7. This result is statistically significant. Males showed larger gains than females, even when the result is expressed as force per kilo body weight. This can be seen in tables 6 and 8. This too is statistically significant. The peak torque recorded during isokinetic test at 60 and 180 degrees/sec increased by an average of 17 % and 22.5 %. These results are shown in table 10 and 12. These results are statistically significant. Again males showed greater gains than females, even when the result is normalised for body weight. This can be seen in tables 11 and 13.

The same training procedure resulted in increases in the velocity of knee extension by an average of 35%. The mean ankle velocity change was much smaller at 8.2 %. These results are shown in table 14 and 15. This result was statistically significant for knee extension. The changes in ankle velocity were non-significant for male volunteers, ($P > 0.5$), and only reached significance at the 0.05 level for female volunteers, ($P > 0.05$).

The maximum acceleration at the knee joint increased by an average of 38.7 %. The increase in acceleration at the ankles was 19.9 %. These results are shown in table 16 and 17. These results are statistically significant for knee joint accelerations but insignificant for ankle joint acceleration changes.

The second series of measurements confirmed the expected changes in knee joint extension torque with different knee angles. However, the measurements of knee velocity under different loads contained a few unexpected results. As can be seen from figure 24, page 81, there was no significant change in knee extension velocity at loads below 50% of the maximum lifted. Above this the velocity slowed progressively. This is a different result from that of the classical observations on the elbow flexors published by Wilkie (1950). He showed that those muscles followed the relationship expected of isolated muscle. This may be due to different mechanical conditions in the two experiments. In Wilkie's experiment, only the elbow joint moves and the flexion is caused by a relatively small muscle mass. In the experiments described here the knee extension is one component of extension of both legs. This requires extension of many joints and many more muscles are activated. Alternatively, it may be related to different neurological control conditions. In this experiment a much larger muscle mass in two limbs is activated than the single muscle group investigated by Wilkie. It is known that the maximum force produced in two leg lifts is less than the sum of the forces produced by either leg alone (Henry & Smith, 1961; Howard & Enoka, 1987). This may reflect a difficulty in maximum activation of large muscle mass.

Discussion of methods used in the training study

In the training study 18 volunteers completed 6 weeks of training, 3 times each week and 3 leg exercises in each session. If the project had included more volunteers and longer training periods, it may well have increased the statistical significance of the results. However, this would have made great demands on the time of the volunteers and the time available for the project was limited. Even with these limitations, statistically significant results were found.

The initial training status of the volunteers was mixed. In general, those who started with the lowest forces, that is the least trained, made the biggest percentage gains in strength. This can be seen from the data shown in tables 5 and 7. The increase in performance, test by test, may be evidence most volunteers complied with training programme. Experiments showed no significant changes in isometric knee extension when volunteers performed 2 tests one week apart with no training programme. These data are reported in table 9, page 46. Thus the increased performance is unlikely to be due to familiarisation with the test procedure.

The training programme consisted of three leg exercises. Volunteers started by lifting at 60% of their one repetition maximum with 12 repetitions, then increased to 70% with 9 repetitions, and then moved to 80% for 5 repetitions. These loads were based on the investigator's personal experience of training at the Ukraine University in Kiev under the direction of Anatoly Poul Bunderchoock. They also were well tolerated by volunteers, none of whom were injured during training. They appear light compared to loads used in other studies where maximum lifts are often reported (Bonde-Petersen, 1960 & Caiozzo et al. 1981). However, it is clear that the training programme produced substantial force gains, even though these might not have been the maximum possible.

Many other studies have used Kin Com dynamometers to test the performance of muscles during movement (Caiozzo et al. 1981; Gregor, Edgerton & Perrine. 1979). However, the Kin Com allowed investigation of only one joint and that at a predetermined velocity. The use of electrogoniometers allowed for several joints to be studied. In addition, since the movement is unrestricted it can be more natural than the singles joint movement investigated on the Kin Com dynamometer. The use of flexible goniometers avoided the need to align the limb with the testing equipment. This allowed unrestrained movement.

The training period in this study was 6 weeks. This is similar to other published studies. The literature contains a great variety of training programmes. The shortest period found was 15 days (Darcus & Salter, 1955) and the longest was 5-6 months (McDougall, Elder, Sale, Moroz & Sutton, 1980). Table 20 lists the details of several papers. There is also substantial variation in the loads used in training. This is also shown in table 20. The lightest load used was 30% of the one repetition maximum (Duchateau & Hainant, 1984) and several authors have used the maximum force in training. There is no clear pattern between the size of training load and the number of repetitions.

Author	**Volunteer**	**Duration**	**Load**	**Force increase**	**Muscle**
Bon-Petersen 1960	17M, 17F	3-5 weeks	10*100%		Elbow flexor, Knee extensor.
Caiozzo 1981	12M, 5F	4 weeks	2*10*100%		Knee extensor
Dons 1979	18M	7 weeks	3*20*50% or 3*12*80%.	12.4% or 42.3%	Knee extensor
Duchateau 1984	20	12 weeks	30-40%, 10times/day	21%	Adductor pollicis.
MacDougall 1980	53M	26 weeks		41%	
Darcus 1955		2 weeks	12*100%	33%	Wrist ext/flex.

Table 22. A summary of previous training study details. M/F indicates male and female subjects. (2*10*100%), indicates2 sets of10 repetitions at a maximum force, i.e. 100%.

The increase in isometric torque at 70° of flexion in this study was 21%. This is similar to the increases in other studies, for example, Rutherford & Jones (1986b) found increases of 15%. Of the 18 volunteers who completed the training programme, all but one (volunteer 18) showed an increase in isometric force. These data are shown in tables 5 and 7. The volunteers were stronger session by session with this one exception. His decline in torques was 10% at 70° and 13% at 60°of knee joint from flexion to extension. He observed the standard training programme. It is not easy to explain his response unless this reflects changes in volunteer 18's technique or motivation. The isokinetic torque data shown in tables 10 and 12 shows more variability. Several volunteers show reduced performances between successive test sessions. Overall, the results show a clear increase in performance for 15 of the 18 volunteers at 60 °/sec and 17 of the 18 volunteers at 180°/sec. Curiously, volunteer 18's decline in isometric torques was also seen at the slower velocity but he showed a clear increase in performance at 180°/sec.

The mean velocity of knee extension increased by 35% in this study. Coyle, Feiring, Rotkis, Cote, Roby, Lee & Wilmore (1981) found torque increases of 32% at a fixed knee exetnsion velocity of 300 °/sec. Caiozzo et al., (1981) and Kaneshi & Miyashita (1983) reported increases of 8% and 24.8% respectively in muscle power at 300 °/sec. These older reports are of muscle power and this is the product force and velocity. In their experiments velocity is fixed and they record force increases. In this case the force is fixed and velocity increases. In both circumstance the power increase is of similar magnitude.

The knee extension velocity data show a similar pattern of variability volunteer by volunteer. Table 14 showed small reductions in velocity. Again this probably reflects underlying variability in technique. The overall pattern shows an increase in velocity session by session.

In contrast, the data obtained for ankle extension velocity is more variable. This is clearly seen in table 15. Six of the eighteen volunteers showed a reduction of their maximum ankle extension velocity over the training period. No statistically significant change in mean ankle velocity is seen over the training period. This is in contrast to the increase in knee extension velocity. Thus, the training must have affected knee and ankle extensor muscles differently. It might be speculated that the exercise programme was more intensive for knee extensor muscles than for ankle extensor muscles.

These results raise an important question: What causes the increases in force and velocity during training? There is no single answer to this. The strength gains in short training studies are usual explained by neural adaptation, the later gains by muscle hypertrophy. The data in table 6 shows that the period of training increases the knee extension torque/kilo body weight by similar amounts in males and females. The data in table 14 shows that the increase in maximum knee extension velocity is not significantly different in males and females. Consequently, there is little difference in the response of male and female volunteers. This agrees with results published by O'Hagan, Sale, MacDougall and Garner (1995). In their study males and females show similar force gains but the proportional increase is greater for the females.

The training period might improve the two-leg co-ordination (Rutherford & Jones, 1986b). It is known that the force produced in two leg lifts is less than the sum of the two single leg maximum lifts (Henry & Smith, 1961; Coyle et al. 1981; Howard & Enoka, 1987, 1991). Training reduces the differences as the two leg lift approaches the sum of the maximum single leg lifts. This might reflect more complete activation of muscles. Improved co-ordination of muscles may also be explained by changes in nervous system (Howard & Enoka, 1987).

In addition to increased activation of knee extensors, it is also possible that there is a decrease in antagonist activity in knee flexor muscles. There is evidence of substantial antagonist activity during slow isokinetic knee extension at 30°/sec (Kellis & Baltzopouls, 1999; Iossifidou & Baltzopouls, 1998; Aagaard, Simonsen, Anderen Magnusson, Bojsen-Moller & Dyhre-Poulsen, 2000). However, the experiments reported here were always conducted at velocities significantly faster than this. There is no literature describing antagonist activity at these speeds.

It can reasonably be supposed that the changes seen in this project are largely due to neural adaptations since the training period was relatively short at six weeks. The possibility of changes such as increased muscle size could occur as a result of increasing fibre size, or increasing fibre numbers or increasing in interstitial connective tissue (MacDougall et. al 1979, 1980; MacDonagh & Davies 1984). An increase in fibre size is known as hypertrophy. An increase in fibre numbers is hyperplasia. Much of the experimental evidence for hyperplasia in response to training comes from animal studies. However, the evidence for hyperplasia in humans is almost completely absent. Sola, Christensen & Martin (1973), Holly, Barnett, & Ashmore (1980), and Alway, Winchester, Davis & Gonyea (1989) have all described the hypertrophy response to resistance training as would be performed by strength or power athletes or body builders. The whole muscle does not respond uniformly to training. Increases in cross-sectional area of both types II fibres and I are seen (MacDougall 1986a). Type II fibres increase more than type I in vastus lateralis (Sale, MacDougall, Jacobs & Garner.1990), and also in biceps brachii (Brown, McCartney, Moroz, Sale, Garner & MacDougall. 1988).

This may reflect a conversion of type I fibres to type fibres II in human skeletal muscle following heavy resistance training (Staron, Malicky, Leonardi, Falkel, Hagerman & Dudley, 1990). Investigations of the training-induced hypertrophy process in human muscle reveal that the larger fibre cross sectional areas are directly related to an increase in both the myofibril area and the myofibril number, with no change in myofibril packing density (MacDougall 1986b). Part of the velocity specific training effect could be related to adaptive changes in the muscle, such as an increase in maximal muscle shortening velocity after high velocity training (Duchateau & Hainaut, 1984). Thus fibre type changes might explain some of the force and velocity increases seen here, but there is no experimental evidence to support this.

The force generated by a muscle depends on the filament overlap and therefore the muscle length. The force generated also varies with the velocity at which it is shortening or lengthening. As the velocity of shortening increases so the force developed by the muscle diminishes. Eventually a velocity is reached at which no force can be developed. This maximum velocity of unloaded shortening is termed V_{max}. The force at zero velocity of shortening, the maximum isometric force is often referred to as P_o. Expressing the force at a particular velocity as fraction of P_o can compare muscles of different sizes and therefore different isometric strength. A wide range of muscle types from species commonly used in experiments can be shown to have similar properties when expressed in this way (Jones & Round, 1990). In particular, the properties of the human elbow flexor group described by Wilkie (1950) closely resemble the properties of isolated muscle. However, the data in this thesis shows departures from this behaviour. In particular 8 volunteers could not make high force – low velocity movements.

The second series of experiments investigated the knee extension velocity under a range of loads up to the maximum each volunteer could lift. All twenty-five volunteers were healthy and they reported no history of training. There was considerable variation in size and weight. Table 18 shows their physical characteristics. Under the minimum loading available with the leg press, the mean velocity was 277 degrees/second. This did not change noticeably until volunteers exceeded about 50% of their maximum. . This can be seen in figure 24 and table 21. The velocity fell progressively under greater loads. It is interesting to note that no low velocity extensions were recorded. All volunteers had a minimum velocity in the range 230.5-114 degrees/sec.

The results obtained in the second series of experiments differ from this pattern. Firstly the velocity was measured as degree/second and secondly the absolute maximum velocity was not very sensitive to load. This can be seen in figure24. The velocity of knee extension does not fall significantly until the load exceeds 100kg. After this the velocity falls with increasing load as might be expected. However, there is a sharp discontinuity in that no volunteer even moved slower than 114°/sec. Each volunteer made three lifts under each load. The fastest knee extension velocity was recorded in each case. Consequently, it is unlikely that the maximum velocity at each load was underestimated as a result of including lifts with poor technique or motivation.

In this study the highest knee extension velocity recorded was 338 degrees/sec (table 15). The weight of the leg press, even when unloaded, was significant. In addition, the weight of the legs must also be considered. This combined load was unavoidable in this experiment and probably accounts for the limit on velocity.

On other hand, very slow velocities should have been obtainable because the muscles should be able to move very slowly under high loads. This is the case for isolated muscle and for Wilkie's (1950) study of human elbow flexors. However, this was never observed in any of the 25 volunteers. Probably a neurological limit, volitional, psychological or reflexive was responsible. Volunteers may have been worried about injury or suffered from loss of motivation. Alternatively, a protective reflex limiting maximum force may have been elicited.

Golgi tendon organs are receptors associated with monitoring muscle force. The sensory fibres from this organ are stimulated by tension within the tendon, whether caused by passive stretching or by contraction of the muscle. They are much more sensitive to active forces. The reflexes elicited by the Golgi tendon organs causing it to relax might inhibit the contraction of the muscle. The "tendon reflex" might protect the muscle from rupturing or tearing by turning off the active development of tension before the tensile stress within the muscle is too great. Some of the strength gains observed in resistance training may occur due to the increased ability of central nervous system to modify such inhibition (McGinnis 1999).

Originally, tendon organs were thought to respond only to large forces and to protect the muscle from overload. However, in animal experiments it has been proved that tendon organs respond to forces as small as those exerted by single muscle fibres or motor units (Houk & Henneman, 1967). Since tendon organs cannot be thought of as specifically sensitive to high forces it is unlikely that they are responsible for protective reflexes (Cleland & Rymer, 1990). The sensitivity of tendon organs to small contractile forces led to a different hypothesis that theses receptors along with the muscle spindle, provide regulation of the muscular stiffness (Houk, 1979). A different line of evidence concerning the function of the tendon organ arose from studies of proprioception and locomotion (Pearson, 1995). These arguments must be treated with caution since they are based on animal experiments. Nothing is known directly about the behaviour of human tendon organs during movement. The possibility that force feedback could be positive during locomotion was intriguing because the pathway arising from tendon organs could explain the loading reflex proposed by Dietz, Horstmann, Trippel & Gollhofer (1989). These are human experiments in which increases in the load supported by the body lead to an enhancement of limb extension. Thus the response to a signal showing increased limb loading is further excitation of extensor motoneurons, This in turn results in increased extensor force (Dietz, Gollhofer, Kleiber & Trippel. 1992). Experiments of this type may lead to a better understanding of the early neural phase of strength gains.

Future plans

This project might be extended to a more complete biomechanical investigation including bilateral measurements and analysis of hip movements. In addition, muscle characteristics such as rate of force developments or fibre size and type could be studied to investigate the precise fibre responses to training. Surveying the muscle properties demands biopsies of human muscles. Further investigation of the nervous system might be done with electromyography to estimate the extent of muscle activation, agonist synchronisation and antagonist inhibition.

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THE EFFECT OF PROGRESSIVE INCREASES IN LOAD ON THE VELOCITY OF KNEE EXTENSION.

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The purpose of this study was to investigate how velocity of shortening of knee extensor muscles was affected by loading. Whilst there is an extensive literature on isolated muscle from laboratory animal species there is very little information about humans. In addition, limb behaviour under voluntary control may differ significantly from isolated tissue maximally activated by electrical stimulation.

Experiments were performed on 25 undergraduate volunteers, 15 males and 10 females. They were selected to represent a cross section of healthy young people rather than on the basis of their training history or status. None had any history of skeletomuscular disorder or significant injury. Each gave informed consent. After a warm up and a period of familiarisation with the task they reclined in a modified leg press machine and were encouraged to lift the applied load by forceful symmetrical leg extension made as fast as they could. The knee angle was measured with a Penny & Giles electrogoniometer spanning the joint. The position signals were digitised at 100 Hz and processed to calculate joint angle, velocity and acceleration. The subjects began with their limb unloaded and on successive trials the load was increased by 20kg until they reached their maximum. Periods of rest between each lift ensured that fatigue played no significant part in determining their performance.

In unloaded conditions, the knee extension velocity was 270 + 50 degrees/sec (mean + SD). The extension velocity did not alter significantly until loads of about 50% of their maximum were applied. The velocity fell progressively at higher loads. These data are illustrated in figure 1. The most unexpected observation was that a minimum knee extension velocity was unexpected high and consistent across all subjects given that the range of maximum loads was between 80 and 280 kilos.. The mean minimum velocity for all subjects under their maximum load was 134 + 34 degrees/sec.

In conclusion, the range of velocities of knee extension appears rather narrow in this study. In particular, the minimum velocity achieved under near maximum load is surprisingly high and consistent across a considerable range of subjects. It might be speculated that this reflects a feature of the voluntary control rather than some intrinsic property of the muscle.

THE EFFECT OF STRENGTH TRAINING ON KNEE AND ANKLE BIOMECHANICS.

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The purpose of this study was to investigate how a 6 week period of strength training affected the isometric strength of knee extensor muscles and the maximum velocity of knee and ankle rotation during weight lifting on a modified leg press machine. There is a significant literature on the increases in muscle force during training but rather less is known about the changes in velocity. Since the power output depends on the product of force and velocity it is interesting to study both features simultaneously.

The experimental protocol was reviewed and approved by the local ethics committee. 25 student volunteers were recruited to the project, 7 dropped out of the study before data collection was completed. Their initial training status was mixed, some were healthy but untrained, other were initially trained for competition at a club level in sports such as judo. At an initial meeting their maximum isometric knee extension forces were measured with a KinCom isokinetic dynamometer, their maximum knee and ankle velocities were measured using lifting manoeuvres on a modified leg press machine using Penny & Giles electrogoniometers spanning their joints. These position signals were digitised at 100 Hz to allow calculation of joint angle, velocity and acceleration. Each individual was assigned a training programme consisting of 3 sessions per week in which the exercised their knee extensor muscles by sets of lifts at 60, 70 and 80% of their single repetition maximum lifts. Compliance with the training programme was assessed by the subjects keeping a training diary and by regular visits of the experimenter to the gymnasium. The tests of maximum isometric force and maximum velocity were repeated at intervals of two weeks throughout the training programme.

From the initial test to tests at week 6, all subjects increased their maximum isometric force. The average increase was 21% + 14.2% (mean + standard deviation). The increase ranged from 3 to 38% with those showing the highest initial forces making the smallest gains. The gains were statistically significant ($p < 0.0001$) when tested with paired t tests. For most subjects the maximum velocity of the knee joint extension increased. The average increase was 31% + 31% (mean + standard deviation). The increase ranged from -13% to 58%. The gains were statistically significant ($p < 0.001$) when tested with paired t tests.

A similar pattern was observed for the maximum velocity of rotation at the ankle joint but the magnitude was less. The average increase in velocity was smaller at 8.3% and the performance was more variable since the standard deviation was 30.4%. The changes ranged from -25% to 64%. The gains in ankle velocity were only weakly significant for the female subjects ($p=0.056$) and were insignificant for the male subjects. The changes in maximum force and maximum velocity appeared uncorrelated.

It appears from these data that our volunteers responded to the training schedule by increasing force in a consistent manner but that the changes in maximum joint rotation velocity were much more variable. Indeed some subjects maximum velocity fell substantially though they had gained experience of making high speed movements. It appears that velocity and force gains are almost independent. It may be imagined that the training programme was more successful in giving the subjects experience of high force generation. Attempts to increase power should also incorporate some specific training in high velocity components of the movement.