POST-MENISECTOMY ATROPHY OF THE QUADRICEPS FEMORIS - THE ROLE OF THE PNEUMATIC TOURNIQUET AND THE EFFECTS OF EXERCISE REHABILITATION.

Thesis submitted to the University of Cape Town

for

MSc (Med)

by

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DECLARATION.

I, M. Nathan, declare that the work on which this thesis is based is original (except where acknowledgements indicate otherwise) and that neither the whole work nor any part of it has been, is being, or is to be submitted for another degree in this or any other University.

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ABSTRACT.

The aim of this study was (i) to investigate the possible role of tourniquet-induced ischaemia in causing the functional impairment of the quadriceps muscle after menisectomy, and (ii) to evaluate the effectiveness of rehabilitation on the restoration of normal quadriceps muscle strength after menisectomy.

Four different research projects were undertaken.

In the first study, female Long Evans rats underwent a one hour tourniquet application to the lower limb in order to simulate the application of the tourniquet used in knee surgery. Groups of rats were then sacrificed 24 hours, ten days, three weeks, six weeks and three months after release of the tourniquet. The gastrocnemius muscle of their tourniquet and control legs were sampled for histological evaluation and for measurement of muscle glycogen levels and the activities of the enzymes phosphofructokinase (PFK) and malate dehydrogenase (MDH).

24 hours after tourniquet release, muscle glycogen levels and PFK activity were significantly lower in the muscles of the limb that had undergone tourniquet-induced ischaemia. There was also early histological evidence of muscle cell degeneration. These changes became progressively more severe with time and were most marked 2 weeks after surgery when there was clear evidence of muscle cell

necrosis. Thereafter, there was muscle cell regeneration which was well advanced by 6 weeks and completed 3 months after tourniquet release.

Biochemical evidence of muscle cell damage paralleled these changes. Thus muscle glycogen levels and muscle phosphofructokinase activity (PFK) were reduced 24 hours after tourniquet release and fell further reaching a naidar after 2 weeks. Levels had returned to near normal by six weeks and were not different from control values three months after tourniquet release. Mitochondrial enzyme activity measured as malate dehydrogenase activity was unaffected by tourniquet ischaemia although 2 weeks after the tourniquet was released, MDH activity was reduced in both tourniquet and control limbs, probably indicating a general reduction in activity of the rat.

In the second study, muscle glycogen levels and quadriceps muscle strength were measured in six randomly-selected patients who had undergone menisectomy up to six weeks earlier but without post-surgical rehabilitation, and in an additional two subjects who had performed a formal exercise rehabilitation programme. Muscle strength, measured with an isokinetic dynamometer, and muscle glycogen levels were reduced in the untrained group but were normal in the trained group when compared to values measured in the control (non-operated) leg. This suggests that the biochemical changes measured in the rat model are probably indicative of

similar changes in human muscle after tourniquet application, and that effective training may reverse these changes.

In the third study, electromyography was used to determine whether the muscle degenerative changes could be due to denervation. 12 post-menisectomy patients were studied on average 7-8 weeks after surgery. Despite the presence of significant muscle weakness, no electromyographic abnormalities were detectable. This indicates either that denervation is not a cause of the post-surgical muscle weakness, or that the denervation had recovered before full muscle recovery had occurred.

In the final study, groups of patients underwent three different methods of rehabilitation after knee surgery under tourniquet. One group received no therapy. A second group underwent a routine post-menisectomy physiotherapy programme. The third group underwent a rehabilitation programme which included isokinetic exercise. The strength of the knee extensors and flexor muscle groups were evaluated 6 weeks after surgery. This study showed significant strength deficits in both the patients who received no therapy and in the patients who underwent a routine rehabilitation programme. The muscle strength of only those patients who had undergone an isokinetic exercise rehabilitation programme had returned to normal.

These studies show (i) that experimental tourniquet-induced ischaemia produces muscle damage that is worst 2 weeks after tourniquet release and recovers by 6 weeks; (ii) that similar changes

probably occur in humans as evidenced by the delayed recovery of muscle glycogen levels and muscle strength in those post-menisectomy patients who do not under an effective exercise rehabilitation programme; (iii) that nerve damage does not explain the muscle weakness present six weeks after knee surgery; (iv) an appropriate exercise rehabilitation programme effects rapid recovery of muscle strength after menisectomy.

ABBREVIATIONS

ADP	Adenosine 5'diphosphate
AMP	Adenosine 5'monophosphate
ATP	Adenosine 5'triphosphate
BSA	Bovine Serum Albumin
CK	Creatine Kinase
F6P	Fructose 6-Phosphate
G6P	Glucose 6-Phosphate
G6PDH	Glucose 6-Phosphate dehydrogenase
HCO_3	Bicarbonate
KOH	Potassium Hydroxide
KPO_4	Potassium Phosphate
LDH	Lactate Dehydrogenase
MDH	Malate Dehydrogenase
M	Molar
m.A.U.	milliamp units
mg	milligrams
$MgCl_2$	Magnesium Chloride
ml	Millilitre
mM	millimolar
mmHg	millimetres of mercury
$NADH^+$	Nicotinamide adenine dinucleotide
NADH	Nicotinamide adenine dinucleotide phosphate (reduced form)
nm	nano metres

CHAPTER I

1. RATIONALE AND SCOPE OF THE THESIS.

2. INTRODUCTION.

1. RATIONALE AND SCOPE OF THE THESIS.

The ability of the patient to return to pre-operative levels of activity following a menisectomy, will to a large degree depend on the post-operative recovery of the strength of the quadriceps muscle. Restoration of quadriceps muscle strength following knee surgery falls within the realm of the exercise therapist. As a practising physiotherapist, I found it disturbing that many of our rehabilitation programmes are based on empirical observations rather than on sound scientific principles.

This I feel has led to the situation that I have observed, in which many surgeons believe that their menisectomy patients recover as quickly when discharged with a home exercise programme as when they attend a routine rehabilitation programme under the care of a physiotherapist. My reading suggests that this observation is in fact true but for the wrong reason. For it seems that patients on a home exercise programme restore their quadriceps muscle strength as badly as do patients attending a routine physiotherapy programme.

I believe that this unhappy situation may reflect a lack of understanding of both the nature and the cause of muscle atrophy following surgery. The traditional theory that atrophy of the quadriceps muscle group after routine menisectomy results from pain and disuse seem unlikely, since today patients are mobilized within a few days after their menisectomy.

This study was thus initiated in an attempt to investigate the above two questions, namely the nature and the cause of muscle atrophy following menisectomy and the role and effectiveness of various rehabilitation programmes in restoring post-surgical strength deficits of the quadriceps muscle. The menisectomy procedure was chosen for three reasons: First, it is the most common surgical procedure amongst sportsmen. Second, sportsmen require the rapid recovery of muscle strength if they are to resume their activities in the shortest possible time. Third, due to the recent advances in surgical techniques, particularly those of partial and arthroscopic menisectomy, the convalescent period after menisectomy has been markedly reduced. This in turn negates the undesirable effects of prolonged post-surgical muscle disuse and shifts the focus of attention to the actual surgical procedure as the cause of muscle functional impairment.

For these reasons, I chose to investigate the possible role of tourniquet-induced ischaemia as a cause of nerve or muscle damage or both after menisectomy; and the effectiveness of various rehabilitation programmes in restoring normal muscle function.

The initial part of the study was concerned with the effects of one hour of tourniquet-ischaemia on rat hindlimb muscle. The time course of recovery was followed both histologically and biochemically for 12 weeks.

The second part of the study focused on post-menisectomy patients. Muscle biopsy samples were taken from the vastus lateralis muscles of both the sound and operated legs of six subjects, all of whom displayed strength deficits of the knee extensors of the operated leg when compared to the control (non-operated) leg. Samples were also taken from two patients who had been rehabilitated. Due to the reluctance of many subjects to submit themselves to the discomfort of the muscle biopsies and the small size of the samples it was decided to measure only the most effective biochemical marker of damage found in the rat, namely muscle glycogen. Samples were taken six weeks after surgery as this approximates the period after which gradual resumption of athletic activity is advised.

In the third part of the study, the vastus lateralis muscles of twelve menisectomy patients were investigated with electromyography to determine whether tourniquet-induced nerve damage could account for post-surgical muscle atrophy.

Finally, the effect of three different rehabilitation programmes on the strength of the quadriceps muscle in three groups of post-menisectomy patients was studied. One group received no formal exercise. The second group were subjected to a routine physiotherapy programme, and the third group underwent a rehabilitation programme involving isokinetic exercise. All subjects were evaluated six weeks after the surgery with a Cybex II Isokinetic Dynamometer (Lumex Inc.). The peak torques generated in the non-operated and

operated legs were measured at two contraction speeds, namely 60° sec^{-1} and 240°sec^{-1}.

2. INTRODUCTION

Menisectomy is one the commonest operations in orthopaedic surgery, accounting for 4% of all orthopaedic admissions in one hospital (Karumo 1977).

Analysis of data of previous studies reveal that between 28 and 80% of knee injuries that result in menisectomy occur during sport; the average incidence is 64% (Appel 1970; Duffin 1977; Duthie and Macleod 1943; Hamberg et al 1983; Jonnson et al 1974; Lysholm and Gilquist 1981; Perey 1962; Shakespeare and Rigby 1983; Wyn-Parry et al 1958 and Yocum et al 1979). Thus menisectomy is argueably the most common orthopaedic operation to which the athlete is likely to be subjected.

The importance of the menisci as load transmitters and thus their role in avoiding stress concentration in the articular cartilage and subchondral bone is now firmly established through the load deflection and or load contact studies of Krause et al (1976), Kurosawa et al (1980), and Walker and Erkman (1975). Distefano (1980) has stressed the importance of the menisci as stabilizers of the knee joint and a total menisectomy has been reported to result in instability of the knee (Huckell 1965; Hughston 1975; Johnson et al 1974; Oretorp et al 1978; Tapper and Hoover 1969; Wang and Walker 1974 and Yocum et al 1979).

In view of the above, it is not surprising that a review of the literature shows that investigators are in agreement that there is an increase in the incidence of degenerative osteoarthritis in knee joints that have undergone menisectomy (Appel 1970; Dandy and Jackson 1975; Fahmy et al 1983; Fairbank 1948; Gear 1967; Hoshikawa et al 1983; Huckell 1965; Jackson 1968; Johnson et al 1974; Tapper and Hoover 1969 and Yocum et al 1979).

Since the post-menisectomized knee joint is anatomically compromised, it is important that the strength and co-ordination of the musculature surrounding the knee joint is normal if the pre-operative level of function is to be regained. The dependency of knee joint integrity on the strength of the quadriceps muscle group has been stressed by Smilie (1971), and good muscle strength can partially compensate for lack of stability (Goldfuss et al 1973).

That marked atrophy and weakness of the quadriceps muscle group develops after menisectomy is well recognized. Of special importance is the capacity for, and time course of recovery of quadriceps muscle strength after menisectomy. A number of investigations have shown that there may be a considerable delay in the return, and even residual impairment of knee extensor strength following menisectomy (Cambell and Glen 1979; Costill et al 1977; Duffin 1977; Hamberg et al 1983; Jenkins et al 1976; Karumo et al 1977; Patel et al 1982 and Prietto et al 1983).

Two questions therefore arise: First, it may be argued that many athletes are returning to sport with sub-optimal muscle strength in one leg and this could account for the high incidence of re-injury in post-menisectomy patients (Sonne-Holm et al 1980). Clearly, the effectiveness of current rehabilitation techniques need to be reviewed. Secondly, the fact that quadriceps muscle weakness occurs even after arthroscopy (Patel et al 1982 and Prietto et al 1983), without direct surgery to the knee or damage to the extensor mechanism, suggests that the operative techniques themselves may cause muscle or nerve damage.

It is the aim of this study to:

1. Investigate the possible role of tourniquet-induced ischaemia in causing the functional impairment of the quadriceps muscle after menisectomy.

2. Evaluate the effectiveness of rehabilitation on the restoration of normal quadriceps muscle strength after menisectomy.

The study was divided into four parts:

1. An animal study to determine the effect of one hour tourniquet-ischaemia and the time course of histological and biochemical recovery in rat hindlimb muscle.

2. An electromyographic study of post-menisectomy patients to determine the incidence of tourniquet-induced nerve damage.

3. A biochemical and functional evaluation of a group of post-menisectomy patients six weeks after surgery.

4. The effect of different rehabilitation programmes on quadriceps muscle strength measured six weeks after menisectomy.

CHAPTER 2

LITERATURE REVIEW

1. THE EFFECT OF MENISECTOMY ON LONG TERM KNEE FUNCTION.

A review of the pertinent literature reveals that studies vary widely in their conclusions regarding the effects of menisectomy on long-term knee function. For example, studies on military personnel show that between 74 and 93% of menisectomy patients were able to return to full duty (Duthie and Macleod 1943; Meekison 1944 and Wyn-Parry et al 1958). Mander (1964) reported that he was able to discharge his 80 subjects with full power and mobility 13 days after menisectomy, and most returned to sport within 3 weeks. Good results have been reported in miners Bonar (1950) and Perey (1962) found that his subjects were able to return to heavy physical labour without any ill-effects. The end result in 80 to 100% of menisectomies has been deemed satisfactory by other workers (Appel 1970; Barford and Bierring 1956; Ferguson and Thompson 1940; Helfet 1963; Lantzounis 1931; Love 1923 and McAusland 1931). Recently Lysholm and Gilquist (1981) reported that 74% of patients who engaged in competitive or recreational sports resumed their activities within 4 weeks of arthroscopic menisectomy.

On the other hand, another study showed that only 26,4% of infantry men were able to return to full military duty following menisectomy (Willien 1945). Tapper and Hoover (1969) and Johnson et al. (1974) respectively rated only 68 and 52,5% of long-term menisectomy results as satisfactory. Huckell (1965) reviewed 462 patients and concluded that 60% of the results were satisfactory if surgery was

performed within one year of injury and 30% were satisfactory if surgery was performed more than one year after injury.

Subjective evaluations of athletic ability after menisectomy reveal that only 50% of athletes rated their post-surgical recovery as excellent (Hoshikawa 1983). In the studies of Sonne-Holm (1980) and Enslin (1983), 27 and 60% of athletes had to either give up or alter their sporting activities following menisectomy. Similarly, only 50% of subjects engaged in sport felt that they had returned to a satisfactory level of competition after isolated lateral menisectomy (Yocum et al 1979).

Thus it would seem that athletes are generally less satisfied with their long-term result after menisectomy and this is likely as a result of the increased demands they place on their potentially unstable knee joints.

2. THE EFFECT OF MENISECTOMY ON THIGH MUSCLE STRENGTH.

Since the late 1960's when isokinetic exercise testing equipment was first introduced, a standardized method for measuring dynamic muscle strength has become available.

Employing the Cybex Isokinetic Dynamometer (Lumex Inc.,) Cambell and Glen (1979) showed 10-12% quadriceps muscle strength deficits on the side of the operated leg, 5-15 months after open menisectomy in patients who had undergone "rehabilitation". Similarly, Costill et al (1977) found that the operated legs were 20% weaker than the non-operated legs even after 6 weeks of training. Another study (Enslin, 1983), showed that even 8 months after surgery all subjects showed significant strength differences between the operated and non-operated legs, even though all had undergone some form of muscle rehabilitation.

Patel et al. (1982) have reported strength deficits of 16 and 9% between the knee extensors of the operated and non-operated leg at testing speeds of 30 and 180 cycles per second respectively, six weeks after arthroscopic menisectomy. Despite this, most subjects had already returned to sport. In this context it is important to note that both Bender et al (1964) and Nicholas et al (1976) have shown that athletes with a quadriceps muscle strength difference between operated and non-operated legs greater than 10%, have an increased risk of re-injury.

Hamberg et al (1983) compared the effect of arthroscopy, with those of open menisectomy, on isokinetic quadriceps muscle strength. They reported that all arthroscopic menisectomy patients had regained their pre-operative levels of muscle strength within 8 weeks. However, muscle strength of the open menisectomy group had still not reached pre-operative values.

In a similar study Prietto et al (1983), showed that both an arthroscopic menisectomy group and an open menisectomy group revealed similar quadriceps muscle strength deficits between the operated and non-operated legs 8 weeks after surgery. Interestingly the arthroscopic menisectomy group had significantly smaller strength deficits than had the open menisectomy group, 20 days after surgery. This was presumably due to less severe surgically-induced pain and discomfort.

Essentially the same results have been shown by other workers. The muscle strength of the operated leg has been reported to be weaker than the non-operated leg, 1.5 (Duffin, 1977) and even 5 to 10 years (Arvidsson, 1981) after menisectomy and knee ligament surgery respectively; even though the latter group included patients whose operative results were rated as excellent by their doctors.

All authors agree that it is primarily the function of the knee extensors which are affected by surgery with relative sparing of the knee flexors (Arvidsson et al 1981; Duffin 1977; Jenkins 1976;

Hamberg et al 1983; Nicholas et al 1976; Patel et al 1982; Prietto et al 1983 and Young et al 1982).

3. SUMMARY OF THE LONG TERM EFFECTS OF MENISECTOMY ON KNEE FUNCTION AND THE EFFECTS OF MENISECTOMY ON THIGH MUSCLE STRENGTH.

The studies on post-menisectomy knee joint function are highly dependent not only on the subjective opinions of both the examiner and the patients, but also on the type of examination performed, whether by a physical examination, a questionnaire, or a combination of both. The variability in the patients occupational and recreational demands also prevent accurate comparisons of these studies, which do not give a realistic indication of the extent or presence of any muscle strength impairment that might account for poor recovery after surgery. However, the measurement of dynamic muscle strength provides a completely objective method for evaluating the effects of menisectomy on thigh muscle strength.

Thus, when measured objectively with dynamic muscle strength testing, the studies reviewed in the previous section clearly show that the strength of the quadriceps muscle is impaired in virtually all post-menisectomy patients, despite their having received some form of rehabilitation.

4. POST SURGICAL MUSCLE FUNCTIONAL IMPAIRMENT - THE ROLE OF THE PNEUMATIC TOURNIQUET.

The advantages afforded the surgeon operating in the bloodless field provided by the pneumatic tourniquet are both numerous and obvious. However, it is frequently overlooked that the pneumatic tourniquet has the distinct disadvantage that it provides the unphysiological environment of increased pressure on the tissues underlying the cuff and ischaemia to all tissues distal to the cuff. Maximum safe tourniquet pressures of 500 mmHg for the lower limb and 300 mmHg for the upper limb are suggested (Cambell 1956). Blood flow to and from the limb distal to a tourniquet is less than 1% of the circulation of the unoccluded limb (Klenerman and Crawley 1977 and Santavirta et al 1978).

The safety of the pneumatic tourniquet with regard to length of application and the pressures used; and the extent to which it may be implicated in post-surgical functional impairment remains a contentious issue. It is clear that the tissues at greatest risk of damage are the muscles and nerves.

4.1 The effect of tourniquet-induced ischaemia on skeletal muscle.

(a) The safe tourniquet time.

Ischaemia of any length of time is harmful to tissues. Largely through empirical observations, 2 hours of tourniquet ischaemia has been regarded as the upper limit of safety (Flatt 1972).

As a "rule of the thumb", Bruner (1970) suggests that 1 hour of tourniquet ischaemia is safe in patients under 40 years of age, on the premise that all biochemical changes induced by tourniquet-ischaemia are fully reversible after tourniquet applications lasting 1 hour. Sanders (1973) asserts that there are no significant microscopic or haematological changes in the ischaemic limbs in animals or man during tourniquet times of less than 4 hours.

(b) Systemic Manifestations of Tourniquet ischaemia.

Chu et al (1976) studied the release of creatine kinase (CK) from the limbs of dogs subjected to various periods of tourniquet ischaemia. Blood CK activity was raised after tourniquet times lasting two to three hours. The rise of CK activity was prevented by short periods of recirculation when the tourniquet was deflated.

In a similar study Santavirta et al (1978) measured blood lactate dehydrogenase (LDH) and CK activity during and 24 hours after surgery in 1000 consecutive operations under pneumatic tourniquet. Although blood CK activity was significantly increased 24 hours after surgery, they concluded that 2 hours of ischaemia is relatively well tolerated.

Modig et al (1978) also measured blood CK activity in patients undergoing surgery with or without tourniquet application. Both groups showed increased blood CK activity after surgery. This

suggests that blood CK activity may not be a sensitive indicator of tourniquet-induced ischaemic muscle damage.

Shaw-Wilgis et al (1971) studied blood P CO_2, P O_2 and pH at 30 minute intervals during tourniquet application and again at 5 minute intervals after deflation. If the tourniquet application lasted two hours or less, all these parameters returned to baseline levels. In a similar study, Modig et al (1978) showed the same result so that both groups Shaw Wilgis (1971), Modig et al (1978) concluded that 2 hours of ischaemia to skeletal muscle is safe.

In contrast, Klenerman et al (1980) have suggested that 3 hours of tourniquet ischaemia is a safe upper limit as they found that blood pH, PO_2, PCO_2, HCO_3^-, and K^+ all returned to normal levels, 40 minutes after even 4 hours of tourniquet ischaemia. Essentially the same findings have been reported by Rorabeck (1980).

(c) Local tissue gas values following tourniquet ischaemia.

The reliability of the conclusions drawn from the latter studies reviewed above depend on the finding that blood values reflect tissue gas values.

To test this, Miller et al (1978) measured tissue and blood gas tensions and pH levels in primates subjected to 1 hour of tourniquet ischaemia. Their results showed that the effect of tourniquet ischaemia on tissue gas tensions was more profound than was suggested by measurements of venous blood gas tensions and pH levels.

Moreover, 5 minutes after deflation of the tourniquet, venous PO_2 was higher than pre-ischaemic and control levels, but tissue PO_2 levels remained less than 60% of pre-ischaemic levels. Thus blood gas tensions may not be representative of the degree and extent of local cellular changes.

(d) Metabolic changes following tourniquet ischaemia.

Stock et al (1971), concluded that rat skeletal muscle was able to tolerate more than 2 hours of tourniquet ischaemia with the tolerance time ranging up to 4 hours. Their conclusions were based on the observations that complete repletion of depleted tissue phosphagen and glycogen stores and restoration of resting lactate levels occurred even after 3 hours of ischaemia. After periods of ischaemia of between 4 and 5 hours, recovery occurred only after 6 weeks.

Haljamae and Enger (1975) and Larsson and Hultman (1979) reported that in humans, concentrations of high energy phosphates and glycolytic metabolites returned to normal levels within 5 minutes after 90 to 130 minutes of tourniquet-induced ischaemia.

In dogs subjected to 3 hours of ischaemia, the metabolism and membrane function of the muscle cells returned to normal 1 hour after tourniquet release (Enger et al 1978).

Paakkonen et al (1981) measured muscle enzymes in 8 menisectomy patients who had undergone approximately one hour of tourniquet

ischaemia. They found that immediately after release of the tourniquet, the activity of the enzymes phosphofructokinase (PFK) and malate dehydrogenase (MDH) were not significantly different from values in the control leg. However on the third post-operative day, the PFK and MDH activities were significantly decreased as compared with the control limb. As these values were not different in the injured and uninjured limb before surgery, this finding indicates that there are significant delayed effects on muscle enzyme activities following tourniquet ischaemia which may have been overlooked by many previous workers.

(e) Histological and histochemical changes following tourniquet ischaemia.

Jozsa et al (1980) and Tountas and Bergman (1977) found no morphological alterations on light microscopy in hand muscles subjected to up to 2 hours of tourniquet ischaemia. In both studies biopsy samples were taken during and at the end of the 2 hours of tourniquet ischaemia. On the other hand, Moore et al (1956) demonstrated advanced degenerative changes under electron microscopy in rat skeletal muscle following 2 hours of tourniquet ischaemia. Samples were examined 20 minutes to 16 hours after tourniquet ischaemia.

Similar results have been found by Harman (1947) in rats and rabbits. Structural changes were found in skeletal muscle after 2 hours of tourniquet ischaemia.

In Rhesus monkeys, Patterson and Klenerman (1979) reported that more damage occured to those tissues lying directly under the tourniquet than to more distal tissues. They noted that the mitochondria appear to be most sensitive to ischaemia and showed mitochondrial structural changes within 1 hour of tourniquet application. Mitochondrial structure returned to normal three days after a 3 hour tourniquet.

Muscle biopsy samples of the quadriceps femoris of dogs taken 2-24 hours after tourniquet ischaemia revealed early degenerative changes even after only 1 hour of tourniquet ischaemia. Granular degenerative changes deteriorated to hyalinization with longer tourniquet times. Furthermore the changes were more severe 24 hours after surgery than they had been 2 hours after surgery (Heppenstall 1979).

In humans undergoing hand surgery under tourniquet, biopsies taken from palmaris longus revealed identical degenerative changes after only 30 minutes of ischaemia. As in the animal studies these changes worsened with increasing tourniquet duration. Delayed changes were not investigated (Solonen and Hjelt 1968).

Sjostrom et al (1982) investigated skeletal muscle morphology following ischaemia in patients undergoing vascular reconstructive surgery in which clamping of the aorta provides the ischaemic insult. Muscle biopsies of the vastus lateralis were taken for morphologic analyses 30 minutes after release of the aortic clamp and

again 5 days later. Aortic clamp time lasted up to 2.5 hours. Abnormalities such as degenerating and regenerating muscle fibres occurred more frequently 5 days than 30 minutes after declamping.

Harman and Gwin (1949) studied ischaemic changes in muscle 15 minutes and 24 hours after tourniquet release. They found a significant increase in degenerative changes 3 and 24 hours after tourniquet release compared to findings immediately after the restoration of blood flow.

In rabbits, Dahlback and Rais (1966) showed degenerative changes within the first 30 minutes following tourniquet ischaemia. The changes were slight as long as the muscle was ischaemic but increased rapidly when the circulation was restored.

Finally, Dahlback (1970) in an extensive study in rabbits demonstrated marked degenerative and regenerative changes after tourniquet ischaemia lasting between 30 minutes and 2 hours. Furthermore some histochemical changes indicative of nerve damage became demonstrable as long as 10-15 days after tourniquet release. Signs of cellular damage were still present 70 days after the tourniquet was released.

(f) Factors potentiating tourniquet-induced ischaemic damage.

The evidence of a number of the above studies indicates that the manifestations of ischaemic morphological changes in skeletal

muscle become most apparent hours and days after restoration of the circulation. The question that arises is, what factors explain this progression of damage?

Post-ischaemic interstitial oedema is a well recognised phenomenon (Bruner, 1970; Lundborg, 1970 and Sanders, 1973) and has been implicated as a cause of delayed muscle cell damage following the application of a tourniquet (Dahlback, 1970 and Harman, 1947). Capillary permeability to protein and fluid is reported to increase when venous PO_2 falls below 10mmHg (Webb 1965).

Interstitial pressures were measured in the anterior tibial and vastus lateralis muscles of primates, subjected to 2 - 5 hours of tourniquet ischaemia. Twenty-four hours after the ischaemic episode, pressures in both muscles were significantly raised compared with controls, even though these pressures had initially returned to normal soon after the tourniquet was released. One hour after tourniquet release, no significant differences in muscle metabolite levels were measured in the vastus lateralis of experimental or control limbs. This finding is similar to responses already responses already reviewed. However, 24 hours later, mean creatine phosphate levels were 34% lower in the experimental muscles (Miller et al 1979).

In earlier studies, Strock and Majno (1969) investigated the vascular responses and micro-vascular changes following 2.5 hours of tourniquet ischaemia in rats. They showed that circulation to the

tibialis anterior muscle was incomplete even though reflow to the skin and other muscles had occurred. This "no reflow" phenomenon was also found, but to a lesser degree, after only 15 minutes of ischaemia. These authors proposed capillary leakage and subsequent oedema as the main explanation for this phenomenon.

Dahlback (1970) repeated the above investigation and concluded that a disturbed circulation persists even one day after ischaemia that lasted 3 hours.

Further evidence that ischaemia may persist after tourniquet release comes from the work of Kennedy et al. (1981). They studied the haemodynamic response to 2 hours of tourniquet ischaemia in dogs and attempted to quantify the degree of arterio-venous shunting before, during and after tourniquet ischaemia. They showed a significant opening of arterio-venous shunts 24 hours after the ischaemic episode, but not during the immediate post-ischaemic period of reactive hyperaemia. Similarly, Edfeldt and Thomson (1980) have also described arterio-venous shunting after tourniquet ischaemia. The effect of this shunting it that it permits little or no oxygen diffusion between capillaries and tissue.

(g) Physiological studies of tourniquet-induced isachemic muscle.

The measurement of contractile properties of skeletal muscle provides a further method for studying skeletal muscle function. Patterson et al (1981) and more recently Gardner et al (1984)

employed these physiological parameters to assess skeletal muscle function following tourniquet ischaemia.

Maximum isometric tension development, contraction and half relaxation times were measured in muscles of primates subjected to 3 and 5 hours of pneumatic tourniquet ischaemia (Patterson et al 1981). There were no consistent differences between control and experimental muscles in contraction and half relaxation times. However, there was a marked decrease in the ability of the muscle to develop isometric tension after 3 hours of tourniquet ischaemia. Furthermore, although an almost normal response was obtained a few minutes after tourniquet deflation, the impaired contractile ability became obvious 24 hours after the ischaemic period. The fall in peak isometric tension was not fully reversed even six days later. Factors such as post-ischaemic interstitial oedema and "no reflow" were cited as causes of the potentiation of the delayed effects of tourniquet ischaemia.

Measuring similar parameters in guinea pigs subjected to 2 hours of tourniquet ischaemia, Gardner et al (1984) showed greatly reduced twitch tension and maximal tetanic tension after the tourniquet was released.

4.2 The Effect of tourniquet-induced ischaemia on nerves.

(a) Nerve Palsy.

The frankest manifestation of nerve damage following the application of the pneumatic tourniquet is a nerve palsy. Since the replacement of the now defunct Esmarch bandage with the pneumatic tourniquet introduced by Cushing (1904), frank nerve palsies are now considered to be a rarity. A review of the literature does however bring to light awareness of the potential for tourniquet-induced nerve palsies.

The results of a questionnaire sent to 150 Australian Orthopaedic surgeons who used both the Esmarch bandage and pneumatic cuff showed an incidence of tourniquet paralyses in the upper limb to be 1 per 1500 applications (Middleton and Varian, 1974). Interestingly, no tourniquet paralyses were reported for the lower limb despite almost 250 000 applications, when the pneumatic cuff was used.

In 1500 consecutive hand operations performed in a bloodless field provided by pneumatic tourniquet, Flatt (1972) reported only 2 tourniquet paralyses. These were subsequently explained on the basis of excessive pneumatic pressure caused by faulty mechanical equipment.

McEwan (1981) reported six cases of tourniquet-induced nerve injury over a period of 18 months. He found four of the tourniquets

involved in these incidents to have been malfunctioning permitting the actual pressure to rise by 150-400 mmHg. The 2 other tourniquet guages had been inaccurately calibrated. A number of studies have confirmed that many cases of tourniquet paralyses are due to faulty equipment Calderwood and Dickie 1972; Fry 1972 and Prevoznik 1937). Irving and Christopher (1984) have highlighted this problem of faulty mechanical equipment as they found that only 2 out of 13 randomly tested pneumatic tourniquets passed their series of calibration tests.

It thus appears that the clinical disaster of nerve palsy is very rare and is due to faulty equipment. But Rudge (1974) reported a case of upper limb paralysis following pneumatic tourniquet induced ischaemia. The pressure measured was 250 mmHg for a duration of one hour and the gauge was said to be accurate. Electrophysiological tests showed that 50% of recovery had not occurred even seventeen weeks after surgery.

Rorabeck and Kennedy (1980) have suggested that tourniquet paralysis is not as rare as the literature indicates and that the medicolegal implications of tourniquet paralysis may account for underreporting. They reported 5 cases of injury to the sciatic nerve as a direct result of tourniquet application to the thigh during knee ligament surgery. Recovery of nerve damage as measured by electromyographic and nerve conduction studies was complete in 6 months in 4 (80%) of the patients.

(b) Nerve conduction.

The measurement of nerve conduction velocity provides a more subtle index of nerve damage than does the clinically obvious sign of nerve palsy.

Using dogs, Rorabeck (1980) measured the conduction velocity along the length of the exposed sciatic nerves. The hind limbs of the dogs were subjected to a tourniquet pressure of 250 or 500 mmHg which was maintained continuously for 1,2 or 3 hours.

At a pressure of 250 mmHg complete nerve conduction block had occurred within the first hour. It took 30 minutes after deflation for the conduction velocity to return to normal. After 1,5 - 2 hours of tourniquet ischaemia at that pressure, it took 45 and 60 minutes respectively for conduction velocity to return to normal. At a pressure of 500 mmHg a complete conduction block occurred within 45 minutes of applying the tourniquet. Conduction velocity returned to normal within 60, 90, and 120 minutes after 1,1,5 and 2 hours of ischaemia respectively. After 3 hours of tourniquet ischaemia, normal conduction had not returned even 2,5 hours after tourniquet deflation. The most severe damage occurred in the segment of the nerve lying directly under the cuff with the least damage occurring in the nerve distal to the cuff.

Electrophysical tests were carried out on 15 ulnar or median nerves in upper limbs subjected to pneumatic tourniquet-induced ischaemia

(Hurst et al 1981). The cuff was inflated to a pressure of 300 mmHg and maintained for a period of 60 minutes. Abnormalities in nerve conduction were observed 5 - 10 minutes after inflation. Recovery of nerve conduction occurred within 5 minutes after deflation. However, conduction time at the level of the cuff, particularly at its proximal border, was only 75% of pre-tourniquet values.

Chu et al (1981) investigated the effects of the pneumatic ankle tourniquet applied for 1 hour at a pressure of 250 mmHg in 40 subjects. Conduction velocities of the peroneal, tibial, sural and medial plantar nerves were measured during, immediately after and 30 minutes after the ischaemic period. Conduction velocities in the studied nerves dropped predictably during ischaemia but returned rapidly to normal following tourniquet deflation. Thirty minutes after tourniquet deflation, all sensorimotor function had returned to normal and the electrophysiological values had returned to 90% of the corresponding pre-ischaemic values.

Fowler et al (1972) followed the recovery of nerve conduction after a pneumatic tourniquet was applied to the hindlimbs of baboons. A pressure of 1000 mmHg was maintained for 1 to 3 hours. In a few cases a pressure of 500 mmHg was also used for a period of 2 hours. In the former study, all nerves showed evidence of conduction block with return to normal occurring only by the 116th day. Severity of nerve damage increased with increased tourniquet times as evidenced by the increase in the incidence of Wallerian degeneration in the

animals subjected to longer periods of tourniquet-induced ischaemia. In the cases where an application pressure of 500 mmHg was used, a normal amplitude response was elicited with an increase in the latency period.

Similarly, Dery et al (1965) demonstrated nerve conduction block in primates after 60 minutes of tourniquet induced ischaemia. Nerve conduction recovered to pre-ischaemic levels 30 minutes after deflation although the latency period remained slightly prolonged.

Lundborg (1970) investigated the recovery of nerve conduction after tourniquet ischaemia. He studied nerves subjected to both ischaemia and compression underlying the tourniquet, and nerves subjected only to ischaemia situated distal to the cuff. After a tourniquet time of 2 hours, recovery was rapid in the ischaemic nerves. There was only minimal recovery of nerve conduction an hour after the tourniquet was released in the nerves subjected to both compression and ischaemia.

(c) "Subclinical" electromyographic changes.

Prompted by the chance observation of electromyographic (EMG) abnormalities in the muscles of a patient with profound muscle weakness following a routine menisectomy, Weingarden et al (1979) set out to determine the incidence of this phenomenon.

Of 25 post-menisectomy patients examined, 18 (72%) demonstrated EMG abnormalities not found in normal patients. The abnormalities included the presence of sharp positive waves or fibrillation potentials, a reduction in the number of voluntary motor unit potentials and an increase in the percentage of polyphasic motor units. They thus concluded that delayed recovery of muscle function may be the result of a slowly resolving axonal compression syndrome. They also showed that muscles supplied by the femoral nerve exhibited the most EMG abnormalities and that the group demonstrating no EMG abnormalities had been subject to an average tourniquet time of only 41 minutes, whereas the average tourniquet time of the 18 patients demonstrating EMG abnormalities was 59 minutes. Serial EMG examinations of 9 of the 18 patients showed complete resolution of the EMG abnormalities within 2 to 5 months.

The above study was extended to include the effects of shorter tourniquet times (Saunders et al 1979). In 15 arthrotomies in which tourniquet times ranged from 11 to 38 minutes, 8 (53%) had abnormal post-operative EMG changes. With tourniquet times ranging from 6 to 16 minutes only one patient (20%) revealed any post-operative EMG abnormalities.

Dobner and Nitz (1982) who noted a wide variation in the time required for patients undergoing identical knee surgery to recover full muscle function performed a similar investigation. Six weeks after menisectomy two groups of patients were investigated electromyographically and functionally. The first group of menisectomy

patients were operated on without the use of a pneumatic tourniquet; the second group had surgery with a pneumatic tourniquet applied in the conventional manner. No patient in the non-tourniquet group showed any post-surgical EMG abnormalities, whereas 71% of the tourniquet group demonstrated abnormal EMG findings. Seventeen of these patients were examined serially and complete resolution of EMG abnormalities occurred between 3 and 6 months after surgery.

Functional tests consisted of comparing the mean vertical jump height in inches of the operated leg compared to the sound leg and the maximal torque generated by the quadriceps femoris muscle group. There was a significant difference between the functional capabilities of the tourniquet and non-tourniquet groups when expressed as a percentage of the sound leg, with the tourniquet group being considerably weaker. Of considerable interest was the finding that there was no significant functional difference when subjects from the tourniquet groups who had no EMG abnormalities were compared with the subjects of the non-tourniquet group. Furthermore, femoral nerve conduction studies revealed no differences between sound and operated legs in the tourniquet group even though quadriceps muscle function was abnormal in 10 of the 17 patients with abnormal EMG changes.

5. SUMMARY OF THE ROLE OF THE PNEUMATIC TOURNIQUET IN CAUSING POST-SURGICAL MUSCLE AND NERVE FUNCTIONAL IMPAIRMENT.

There is little doubt that tourniquet ischaemia of greater than 4 hours may lead to irreversible damage of skeletal muscle. It is also clear that the incidence of frank nerve palsies following tourniquet application are rare and invariably due to faulty mechanical equipment. However these considerations do not explain the muscle atrophy seen after routine menisectomies in which the tourniquet time rarely exceeds an hour and the incidence of frank nerve palsies are excessively rare.

However, it seems likely that degenerative changes in muscle after 30 minutes of tourniquet ischaemia and factors potentiating ischaemia such as oedema and arterio-venous shunting combined with subclinical EMG changes are likely factors explaining the muscle atrophy. Peltier (1979) has suggested that since such obvious damage as ischaemic contractures have been eliminated with the replacement of the Esmarch bandage with the pneumatic tourniquet, investigations should now be looking at subclinical complications and the role of rehabilitation in post-surgical muscle recovery.

For the sake of clarity, the effects of tourniquet ischaemia on muscle and nerve have been reviewed separately, and it is unclear whether the overiding cause of muscle damage is as a direct result of ischaemia or is secondary to nerve damage. It is also unclear

whether nerve damage occurs as a result of direct pressure or is also due to ischaemia.

Dahlback (1970) compared the damage in muscle after crushing the peronial nerve or applying a tourniquet and found the damage to be equally severe in both cases. In the muscles subject to tourniquet ischaemia there was evidence of both ischaemic muscle damage and later delayed changes indicative of denervation were also detected. These denervation changes were as severe as those demonstrated in the muscles whose nerve was crushed. He concluded that ischaemia to the peripheral nerves caused denervation which then resulted in the observed changes in the muscle. Other studies have also implicated direct pressure on the nerve as a prime cause of tourniquet induced nerve damage (Ochoa et al 1972 and Lundborg 1970). Regardless of the initial insult damaged muscle follows a similar course of degeneration followed by regeneration (Carlson 1983).

6. THE ROLE OF REHABILITATION.

The increase in technical excellence of the knee surgeon must be met with similar innovations in rehabilitation techniques, if the patient is to benefit maximally.

As reviewed in a previous section, the normal muscle strength of the quadriceps returns very gradually if at all after a "simple" menisectomy. In the studies of Cambell and Glen (1979), Costill et al (1977) and Enslin (1983), rehabilitation failed to restore the quadriceps muscle strength of the operated leg to that of the unaffected leg.

However, the importance of effective rehabilitation is not widely appreciated. Seymour (1969) studied two groups of post-menisectomy patients. One group received no formal physiotherapy after being discharge from hospital, while the experimental group received physiotherapy. The groups were compared after various periods up to three months after surgery with respect to the presence of effusion, range of knee movement, mid-thigh circumference and time to return to work and to recreational activity. As there were no significant differences between the groups, Seymour concluded that "post-operative physiotherapy in the routine case is of no value"; thus implying that in the "routine" case, knee muscle strength and function returns to normal without the need for any formal exercise programme. But no measurements were made to compare the quadriceps muscle strength of the operated and control legs. Had this been

done, the most likely conclusion would have been that the physiotherapy programme was unable to reverse the muscle atrophy resulting from surgery. O'Donoghue (1980) has made a similar error by stating that there are many cases of "simple" menisectomy in which an intelligent patient can follow a simple therapy guide given on discharge without the need for formal physiotherapy.

But Karumo et al (1977) performed a similar investigation in which muscle strength was measured. They compared the strength and histological appearance of the quadriceps before and four weeks after menisectomy in two groups of patients. One group received routine physiotherapy while the other group (intensive physiotherapy) received the same programme, but twice daily. Their results showed equally marked quadriceps weakness and decreased areas of both Type I and type II muscle fibres in both groups of patients, compared to the pre-operative measurements.

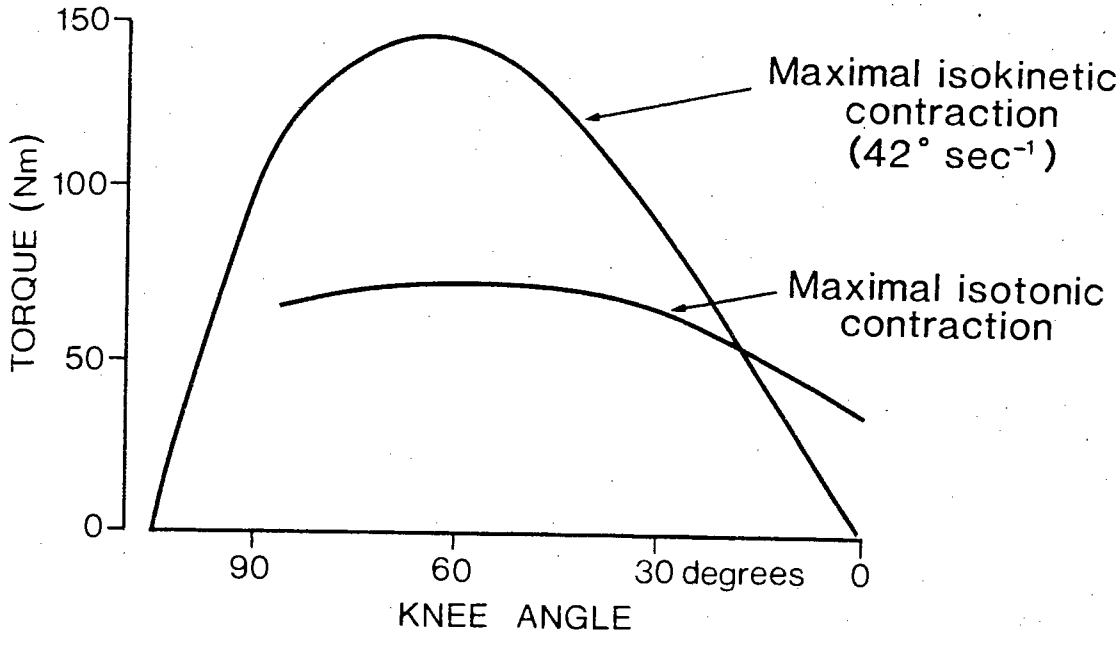
It should also be noted that Appel (1970) found that patients who had received post-operative muscle training developed a significantly lower incidence of radiological degenerative changes of the knee.

6.1 "Effective" rehabilitation - isokinetic rehabilitation.

Fortunately there is a novel innovation for exercise rehabilitation. This takes the form of isokinetic exercise equipment, originally developed by Hislop and Perrine (1967). This type of

exercise involves a muscle working concentrically at a fixed speed against variable accommodating resistance, and has a number of advantages over the more conventional methods of muscle strengthening, namely isotonic and isometric muscle contractions. In an isokinetic rehabilitation programme maximal resistance can be achieved throughout the entire range of motion, whereas in a conventional (isotonic) weight training programme the torque will be maximal only for part of the range of joint motion. This is because in weight training the load on the muscle is fixed whereas the strength of the muscle will vary considerably throughout its range of motion. Fig 2.1 demonstrates this concept by comparing the mechanisms of an isokinetic contraction with those of an isotonic contraction against a constant load (weight). It is clear that in an isotonic contraction, maximal torque is produced by the muscle only at the extremes of its range of motion, at which ranges a muscle seldom works during normal activies.

FIG 2.1.



A comparison of the torques produced during a maximal isokinetic knee-extension (upper curve) and during a maximal isotonic contraction at the same average velocity using a weight arranged to give maximal torque at a knee angle of 60°. Note that the peak torque produced during isokinetic contraction greatly exceeds that during the isotonic contraction. (Data from Grimby 1982).

Specificity of speed is also an important factor to be considered during muscle training. Studies have shown that improvements in strength are speed specific (Caiozzo et al 1981 and Coyle et al 1981). In other words in order to strengthen a muscle to perform at for example 240° sec^{-1}, training of that muscle should occur at 240° sec^{-1}.

This is of particular importance in rehabilitation as it has been shown that exercise in which maximal torque is produced at high velocities causes recruitment of predominantly the type II muscle fibres (Coyle et al 1981 and Thorstensson et al 1976). Although some studies show a predominant atrophy of type I muscle fibres following knee ligament surgery and immobilization (Edstrom 1970 and Haggmark et al 1981); other workers have found a reduction in type II muscle fibre area after knee surgery and injury (Baugher et al 1984, Grimby et al 1980 and Young et al 1982).

It is thus obvious that rehabilitation programmes should include muscle strength training at all speeds. This is possible using isokinetic exercise equipment, but not with a normal weight training (isotonic) programme. Since most sporting activities are performed at relatively fast speeds of contraction, so re-training to strengthen weak muscles should include higher speeds of muscle contraction.

Isokinetic rehabilitation is also safer than weight training particularly in the early rehabilitative phase when the muscle is weak

and easily fatiqued, because the resistance in isokinetic exercise is accommodating so that it is impossible to overload either the muscle or joint.

6.2 Isokinetic rehabilitation vs. isotonic rehabilitation.

The above advantages of isokinetic rehabilitation are all theoretical. However, there are practical studies confirming the effectiveness of this form of rehabilitation.

Studies have compared gains in both muscle strength and improvements in motor performance after isokinetic and isotonic muscle training programmes. (Pipes and Wilmore 1975 and Smith and Melton 1981). Both studies showed that the gain in muscle strength was significantly greater in the isokinetically trained groups. It is interesting to note that the subjects who trained at fast isokinetic speeds showed the greatest improvements in motor performance tests which included a vertical jump test and a 40 metre dash.

Grimby et al (1980), compared the effect of weight training and isokinetic training in patients following knee ligament surgery. Interestingly before training commenced, knee extensor strength about a year after surgery was about 20% of the non-operated leg even though all subjects had resumed athletic training. The results showed that the isokinetically trained group had the largest strength increases after six weeks of training.

Sherman et al (1983) have shown that an appropriate isokinetic rehabilitation programme restores quadriceps muscle strength within 6 weeks of menisectomy.

6.3 Endurance.

Motor performance depends not only on muscle strength but also on muscle endurance. Isokinetic training has been shown to increase muscle endurance by 8% after a 20 week training programme (Gettman et al 1980). This however is a small increase compared with that expected after an aerobic activity such as cycling or running for a similar duration.

Costill et al (1977) measured the succinate dehydrogenase (SDH) activity of the vastus lateralis muscles as an indication of aerobic capacity in two groups of post-menisectomy patients. One group was rehabilitated using weight training, while the other group supplemented the resistance training with 20 to 30 minutes of cycling daily. Analysis of the biopsy specimens showed that after 6 weeks of training the subjects that trained only with weights had lower SDH activities in the muscles of the operated compared to the non-operated leg. In contrast, the SDH activity of the vastus lateralis of the group that both cycled and trained with weights had returned to normal.

These studies indicate that a rehabilitation programme should also include an endurance activity. As far as knee rehabilitation is

is concerned, cycling is the most appropriate form of exercise as it avoids the added stress of weight bearing.

6.4 Pre-operative muscle training.

It has traditionally been accepted that the ideal post-surgical knee rehabilitation programme should include pre-operative muscle training. However studies have shown that pre-surgery muscle strength has no influence on muscle strength post-surgery (Jenkins et al 1976 and Karumo et al 1977). This is to be expected if tourniquet-induced damage causes the post-surgical muscle weakness. It is difficult to conceive how muscle training before surgery could influence the extent of this damage.

7. SUMMARY OF THE ROLE OF REHABILITATION.

Although most studies of the effect of training on quadriceps muscle strength after knee surgery show that a routine physiotherapy rehabilitation programme does not reverse the surgically induced mucle atrophy, it has been shown that when an effective rehabilitation programme is instituted, quadriceps muscle strength may be regained within six weeks after an open menisectomy.

An effective rehabilitation programme should include isokinetic muscle contractions at all speeds as well as aerobic exercise such as cycling to enhance the endurance capacity of the muscle. At a later stage normal weight training should also be used since one of the disadvantages of isokinetic muscle contractions is that they do not produce eccentric muscle contractions, which are essential in normal activities for the control and deceleration of movement around a joint.

CHAPTER III

EXPERIMENTAL METHODS AND MATERIALS

1. THE BIOCHEMICAL AND HISTOLOGICAL CHANGES IN RAT HINDLIMB MUSCLE FOLLOWING ONE HOUR OF TOURNIQUET ISCHAEMIA AND THE TIME COURSE OF RECOVERY.

1.1 Animals:

Female Long Evans rats weighing 300-400g were used.

1.2 Experimental Procedures:

The animals were anaesthetised with Pentobarbitone Sodium (Sagatal, Maybaker). A dosage of 6mg/100g was used.

Tourniquet ischaemia was induced by lapping No.32 Judron rubber-bands eight times on a thin walled tube. The rat's leg was pulled into the tube and the band pushed high on the thigh. The tourniquet was left on the thigh for a period of an hour, and then removed.

The animals were then placed in cages and allowed to recover in an animal house maintained at a temperature of 22°C and placed on a normal ad libitum rat Lab Chow diet.

Twenty four hours, ten days, three weeks, six weeks and three months after the tourniquet-induced ischaemic bout, six rats in each group were anaesthetised using the same procedure as above. Samples of the gastrocneumius muscle were removed from a site distal to the previously applied tourniquet. Samples from an identical site of the unaffected leg served as the control muscle.

The animals were sacrificed with an overdose of anaesthetic.

The samples were then divided and subjected to three different methods of preparation.

One sample was immediately placed in liquid nitrogen and stored at -80°C for subsequent analysis of muscle glycogen content and phosphofructokinase (PFK) activity. A second sample was placed in an ice cold phosphate buffer and washed free of blood. The sample was then placed in liquid nitrogen for subsequent determination of malate dehydrogenase (MDH) activity. MDH activity was measured in muscles sampled 24 hours, 10 days, 2 weeks and 6 weeks after the tourniquet was released. For a detailed account of the biochemical assay methods refer to Appendix I.

A third sample was orientated on a piece of blotting paper and allowed to stand for approximately thirty minutes to allow relaxation of the contractile elements. The sample was then placed in 10% buffered formalin for a few days. Later the sample was embedded in paraffin wax, sectioned at 5μ on a microtome and prepared for light microscopy. The slides were stained for haematoxylin and eosin (H and E).

Alternatiely some of the samples were prepared for histology using frozen sections. The muscle samples were orientated, covered with talcum power (to minimize freezing artifact) and allowed to stand for approximately 30 minutes. The samples were then frozen in

liquid nitrogen (-80°), cut on a cryostat and picked up on a cover slip. These sections were also stained with H and E.

The histological appearance of the muscles were examined in these muscle sampled 24 hours, 10 days, 2 weeks, 6 weeks and three months after the tourniquet was released.

1.3 Statistical methods used.

Paired data were analysed according to the one-tailed Mann U Test. A p value <0.05 was considered statistically significant.

2. THE BIOCHEMICAL AND FUNCTIONAL CHANGES IN THE QUADRICEPS MUSCLE OF A GROUP OF POST-MENISECTOMY PATIENTS, SIX WEEKS AFTER SURGERY.

2.1 Subjects.

Six post-menisectomy patients under the care of several orthopaedic surgeons were contacted and requested to volunteer to participate in the study. The subjects had not undergone any formal rehabilitation programme, but were instructed by their respective surgeons on home exercises to increase the strength of the knee extensor and flexor muscle groups. A further two subjects, J.G. and SvG. who had undergone an intensive isokinetic rehabilitation programme also volunteered to participate in this study. Table 3.1 lists the ages and sex of the patients and the type of menisectomy procedure they underwent.

TABLE 3.1

SUBJECT	AGE	SEX	MENISECTOMY PROCEDURE
S.S.	23	M	Total left medial
D.H.	18	M	Total right lateral
M.W.	18	M	Total right medial
J.B.	35	M	Total right medial
A.L.	24	M	Arthroscopic left medial
D.A.	22	M	Partial left medial
*J.G.	28	M	Total left medial
*SvG.	32	M	Total right medial

* denotes subjects who participated in a formal isokinetic rehabilitation programme. All other subjects underwent no formal post-operative rehabilitation.

2.2 Experimental Procedures.

(a) Muscle strength testing.

Six weeks after surgery the muscle strength of the knee extensors and flexors of both legs were measured, using a Cybex II Isokinetic Dynamometer (Lumex Inc.).

Before testing the subjects warmed up for five minutes on a stationary exercise cycle.

The unaffected leg was always tested first. The patient was positioned on the Cybex knee testing table with the thigh fully supported and the knee flexed to at least 90°. The lever arm was secured to the patient via the shin pad placed just proximal to the malleoli. In order for the movement to be isolated to the knee joint a velcro strap stabilized the thigh and another strap stabilized the upper body. During the movement, subjects were instructed to fold their arms. The fulcrum of the lever arm was positioned in line with the axis of rotation which corresponds to a transverse line through the femoral condyles. The subjects were allowed 5-10 familiarization repetitions before testing took place at each speed. Testing speeds of $60°sec^{-1}$ and $240°\ sec^{-1}$ were used. At $60°sec^{-1}$ the subjects were verbally encouraged to extend and flex the knee maximally for five repetitions. At $240°sec^{-1}$ the subjects were verbally encouraged to maximally extend and flex the knee for twenty-five repetitions.

The maximum torque produced was recorded on a pen recorder chart and measured in Nm.

The same procedure was repeated on the operated leg. The subjects were instructed to state whether any discomfort was felt in the knee as pain would obviously influence the maximum torques produced.

(b) Muscle Biopsies:

Within a few days of the muscle strength tests, the subjects underwent two muscle biopsies. Two incisions (one on each leg) were made under local anaesthesia through the skin into the superficial fascia overlying the distal third of the vastus lateralis muscle. A muscle biopsy sample was taken according to the procedure of Bergstrom (1962), as modified by Evans et al (1982). The tissue was immediately frozen in liquid nitrogen and stored at -80° for later determination of muscle glycogen content. Due to the reluctance of many subjects to endure the discomfort of the muscle biopsies and because of the small size of the samples it was decided to measure only the best predictor of damage following tourniquet ischaemia in the rat, namely, muscle glycogen.

For a detailed account of the procedures used to determine the muscle glycogen content refer to Appendix I.

2.3 Statistical methods used.

Paired data were analysed according to the one-tailed Mann-Whitney U test. A p value $<0,05$ was considered to be statistically significant.

3. AN ELECTROMYOGRAPHIC STUDY OF POST-MENISECTOMY PATIENTS.

3.1 Subjects.

Twelve post-menisectomy patients under the care of several orthopaedic surgeons were contacted and requested to volunteer to participate in this study. When tested on a Cybex Isokinetic Dynamometer or an Orthotron II (Lumex Inc.), all but two of the patients demonstrated strength deficits of the knee extensors of the operated leg when compared to the non-operated leg.

Table 3.2 lists the subjects' ages, sex, time after surgery when the examination took place and the type of menisectomy procedure they underwent.

3.2 Experimental Procedures.

The electromyographs were performed in the Department of Neurology, Groote Schuur Hospital by a skilled technician. A Modic Electromyograph was used. Using a concentric monopolar needle electrode, the vastus medialis muscle was investigated at four sites spanning the length of the muscle.

The criteria for abnormalities were those adopted by Dobner and Nitz (1982), namely the presence of spontaneous activity at rest (fibrillation potentials, positive sharp waves and bizarre high frequency discharges), or an increase in the number of polyphasic motor units above 30% with minimal contraction.

The electromyograph was equipped to produce a printout which provided a permanent record of each test. These were examined by the author and by a neurologist experienced in clinical electromyography.

TABLE 3.2

SUBJECT	AGE	SEX	TIME FROM SURGERY TO EXAMINATION (WEEKS)	MENISECTOMY PROCEDURE
D.A.	22	M	4	Partial left medial
J.G.	28	M	6	Total right medial
D.H.	17	M	12	Total right lateral
M.W.	17	M	12	Total right medial
D.S.	29	M	6	Total left medial
R.L.	35	M	6	Total right medial
S.M.	27	M	4	Total left lateral
R.P.	22	M	8	Partial left medial
J.M.	32	F	4	Total left medial
C.S.	28	F	12	Total right medial
S.S.	23	M	6	Total left medial
J.R.	35	M	7	Total right medial

4. THE EFFECTS OF REHABILITATION ON THE MUSCLE STRENGTH OF POST-MENISECTOMY PATIENTS, SIX WEEKS AFTER SURGERY.

4.1 Subjects.

Fifteen post-menisectomy patients under the care of several orthopaedic surgeons were contacted and asked to participate in this study. The subjects were assigned to one of three groups, depending on the post-operative rehabilitation programme they underwent. Group I (n=5) received no formal rehabilitation programme, Group II (n=5) underwent a routine post-menisectomy physiotherapy programme, Group III (n=5) underwent an exercise rehabilitation programme that made use of isokinetic equipment. All subjects were aware of the importance of performing static bracing of the knee extensors and straight leg raising exercises post-operatively.

Table 3.3 lists the subjects' ages, sex and the type of menisectomy procedure they underwent.

4.2 Experimental Procedures.

The subjects in groups II and III began their respective rehabilitation programmes approximately 10 days after surgery, as soon as their sutures had been removed.

The routine physiotherapy programme to which the subjects in group II were assigned, was performed at the Physiotherapy Out Patient

Department of Groote Schuur Hospital under the guidance of a physiotherapist. The programme consisted of graded muscle strengthening exercises 3 times per week. This included resistance training utilizing a Westmister Pulley apparatus. Three sets of 12 repetitions were followed by 3 sets of 25 repetitions using a lighter weight. Cycling was also included. Initially, patients performed 15 minutes of cycling on a stationary ergometer. This was rapidly increased until the subjects were cycling for 30 minutes during each treatment session. Step-up exercises were introduced gradually.

The isokinetic rehabilitation programme to which the subjects in group III were assigned, was performed at the S.A.B. Sports Injury Clinic at U.C.T. under the guidance of a physiotherapist. The programme was adapted from that of Sherman et al (1982). In brief, it consisted of 2 sets of isokinetic muscle contractions on an Orthotron II (Lumex Inc.,) at slow, medium and fast speeds of muscle contraction. Initially the slower speeds were used and only later were speeds of up to 270° sec^{-1} introduced. Each set was performed until the torque developed had declined to half that produced by the first contraction. A cycling regime was also included. Subjects in both training groups exercised three times per week. Both rehabilitation programmes were carried out until the end of the sixth post-operative week.

Six weeks after surgery the muscle strengths of the knee extensor and flexor muscles of both the operated and non-operated legs were

tested according to the procedure already described (refer to part 2 of this chapter).

TABLE 3.3

SUBJECT	AGE	SEX	MENISECTOMY PROCEDURE
GROUP I - NO REHABILITATION.			
A.A.	27	M	Partial right medial
S.S.	23	M	Total left medial
K.L.	28	M	Partial right medial
J.S.	26	M	Partial right medial
J.R.	35	M	Total right medial
GROUP II - ROUTINE REHABILITATION.			
H.N.	26	M	Partial right medial
D.G.	24	M	Partial left medial
A.R.	24	M	Total right medial
P.T.	25	M	Partial right medial
D.L.	23	M	Total right medial
GROUP III - ISOKINETIC REHABILITATION.			
J.G.	28	M	Total left medial
S.vG.	32	M	Total right medial
D.S.	29	M	Total left medial
G.G.	24	M	Total left medial
E.G.	25	M	Partial right lateral

4.3 Statistical methods used.

Unpaired data were analyzed according to the one-tailed Mann-Whitney U Test. A p value $<0,05$ was considered to be statistically significant.

CHAPTER IV

EXPERIMENTAL RESULTS

1. THE BIOCHEMICAL AND HISTOLOGICAL CHANGES IN RAT HINDLIMB MUSCLE FOLLOWING ONE HOUR OF TOURNIQUET ISCHAEMIA AND THE TIME COURSE OF RECOVERY.

1.1 Biochemical changes.

(a) Muscle glycogen levels.

Table 4.1 lists the muscle glycogen levels in the gastrocnemius muscles of rats subjected to one hour of tourniquet ischaemia. The levels were measured 24 hours, 10 days, 2 weeks, 3 weeks, 6 weeks and three months after the tourniquet was released. In each group of rats (n=6), the unaffected leg served as the control. The corresponding mean values (± S.E.) are depicted in Figure 4.1.

The glycogen levels were significantly decreased ($p<0.05$) in the tourniquet leg 24 hours after the tourniquet was released. Between the tenth and fourteenth day after the tourniquet was released, the glycogen levels in the tourniquet limb dropped even further. A gradual recovery then occured, and only three months after tourniquet release was there no significant difference in the muscle glycogen levels between the tourniquet and control legs.

(b) Muscle phosphofructokinase (PFK) activity.

Table 4.2 lists the muscle PFK activities in the gastrocnemius muscles of rats subjected to one hour of tourniquet

TABLE 4.1

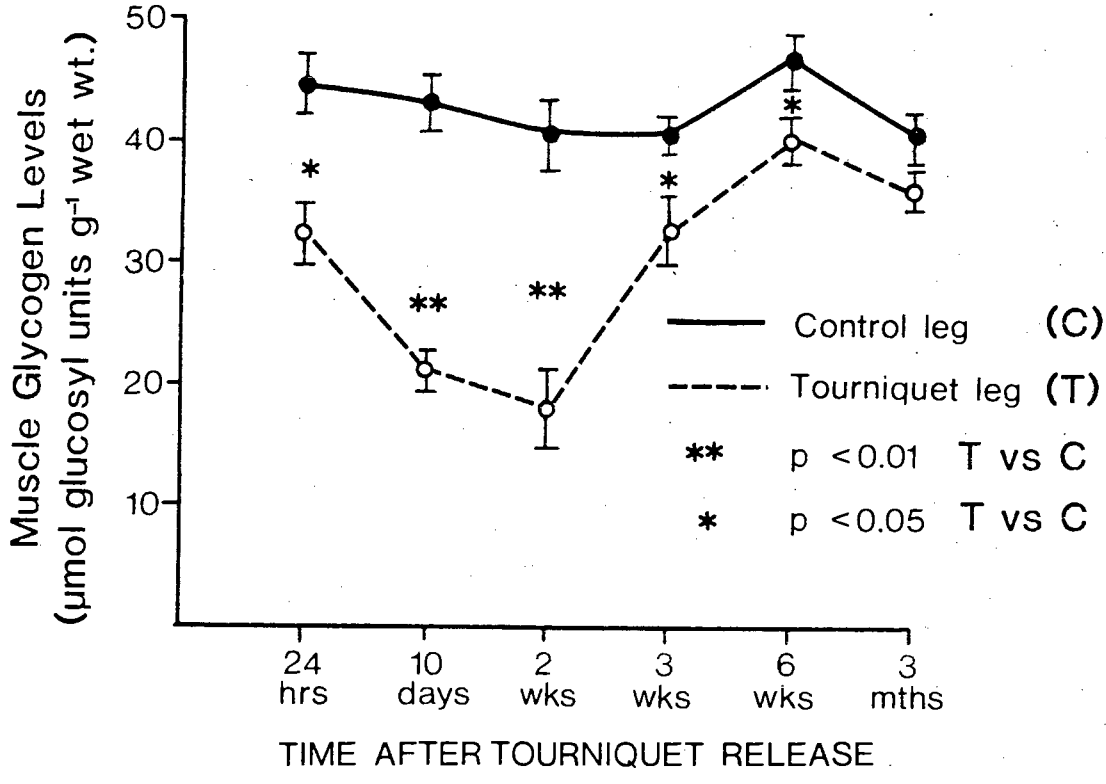
MUSCLE GLYCOGEN (μmol glucosyl units g^{-1} wet weight) LEVELS IN RAT GASTROCNEMIUS MUSCLE AT VARIOUS TIMES AFTER ONE HOUR OF TOURNIQUET-INDUCED ISCHAEMIA.

TIME AFTER TOURNIQUET RELEASE											
24 HOURS		10 DAYS		2 WEEKS		3 WEEKS		6 WEEKS		3 MONTHS	
T	C	T	C	T	C	T	C	T	C	T	C
38.3	54.1	18.6	46.5	11.2	29.7	45.5	41.8	40.8	47.1	37.9	34.9
28.4	39.7	20.6	35.4	7.9	53.3	33.1	44.1	47.7	58.0	35.6	39.2
23.1	41.0	27.3	50.7	19.3	37.6	29.9	40.3	34.9	43.7	37.7	46.8
29.9	40.2	17.2	40.2	15.6	40.7	29.7	34.2	40.6	45.3	29.6	35.7
37.8	46.2	21.3	43.3	26.4	43.9	33.4	42.7	38.9	43.1	35.1	39.2
36.4	44.5	22.8	43.4	28.3	37.8	25.0	39.3	37.6	42.3	40.8	44.8
MEAN 32.3*	44.3	21.3**	43.2	18.1**	40.5	32.7*	40.4	40.1*	46.6	36.1	40.1
S.E. 2.5	2.2	1.5	2.1	3.3	3.2	2.8	1.4	1.8	2.4	1.5	2.0

* $p<0,05$ Tourniquet (T) vs control (c) limbs.
** $p<0,01$ Tourniquet (T) vs control (c) limbs.

FIGURE 4.1

MUSCLE GLYCOGEN LEVELS (μmol glucosyl units g^{-1} wet weight) IN RAT GASTROCNEMIUS MUSCLE AT VARIOUS TIMES AFTER ONE HOUR OF TOURNIQUET ISCHAEMIA.



NOTE THAT EACH POINT REPRESENTS THE MEAN ± S.E. FOR SIX MEASUREMENTS.

ischaemia. The activities were measured 24 hours, 10 days, 2 weeks, 3 weeks, 6 weeks, and three months after the tourniquet was released. In each group of rats the unaffected leg served as the control. The corresponding mean values (± S.E.) are depicted in Figure 4.2.

Muscle PFK activity was also significantly lower in the tourniquet limbs 24 hours after tourniquet ischaemia and only 3 months after the tourniquet was released had PFK activities returned to control values in the tourniquet limb.

The fall in PFK activities of the tourniquet leg followed closely the pattern in the corresponding muscle glycogen levels and the muscle PFK activities were lowest betweeen 10 and 14 days after the tourniquet was released (Figure 4.2).

(c) Muscle malate dehydrogenase (MDH) Activity.

Table 4.3 lists the muscle MDH activities in the gastrocnemius muscles of rats subjected to one hour of tourniquet ischaemia. The levels were measured 24 hours, 10 days, 2 weeks, and 6 weeks after the tourniquet was released. In each group (n=6), the unaffected leg served as the control. The corresponding mean values (± S.E.) are depicted in Figure 4.3.

TABLE 4.2

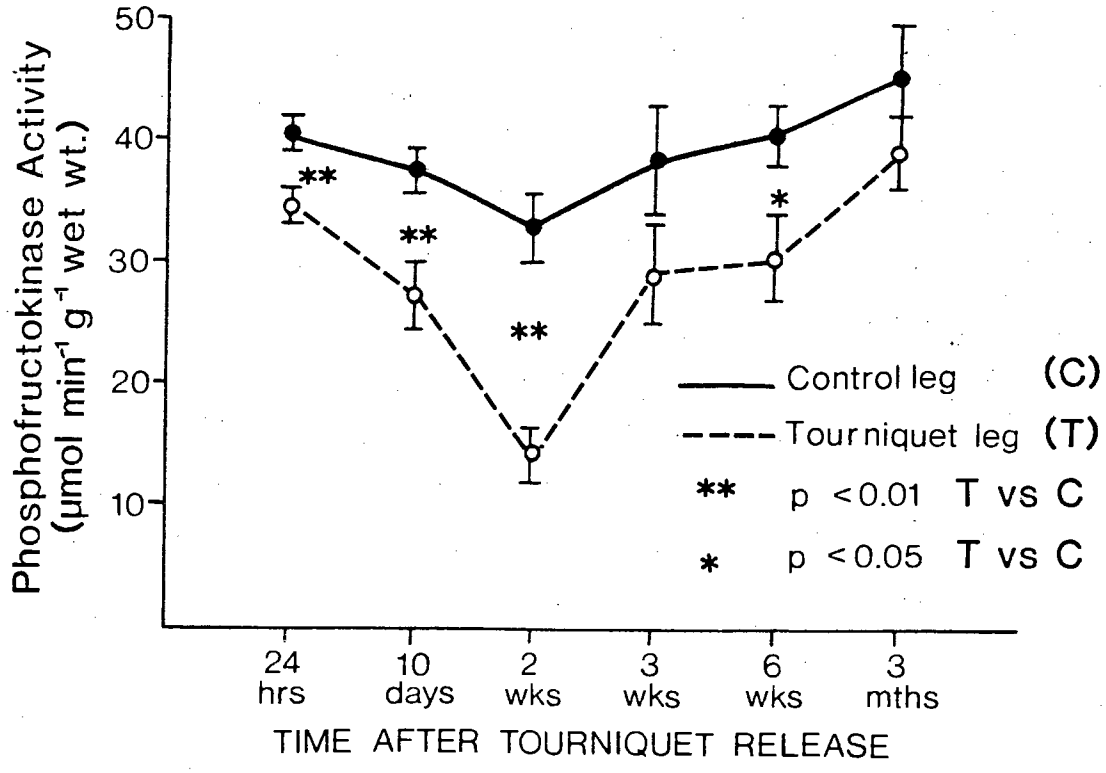
($\mu mol^{-1} min^{-1} g^{-1}$ wet weight) MUSCLE PHOSPHOFRUCTOKINASE ACTIVITY IN RAT GASTROCNEMIUS MUSCLE AT VARIOUS TIMES AFTER ONE HOUR OF TOURNIQUET-INDUCED ISCHAEMIA.

TIME AFTER TOURNIQUET RELEASE											
24 HOURS		10 DAYS		2 WEEKS		3 WEEKS		6 WEEKS		3 MONTHS	
T	C	T	C	T	C	T	C	T	C	T	C
35.4	42.2	20.7	36.6	14.0	30.4	34.5	48.3	24.2	41.4	44.9	41.8
36.6	43.4	20.0	37.8	8.2	39.0	44.5	55.2	38.6	47.3	41.8	49.9
28.5	40.1	37.4	39.2	7.8	29.2	25.5	33.8	29.3	38.3	46.6	58.7
37.1	36.2	29.3	30.8	16.3	30.6	13.9	25.2	33.8	44.5	27.6	29.3
34.9	40.0	33.0	40.0	20.8	42.0	27.0	34.5	17.8	29.3	40.7	51.8
36.2	42.5	22.5	42.3	18.6	25.3	28.5	33.4	39.7	41.9	33.7	41.4
MEAN 34.8**	40.7	27.2**	37.8	14.3**	32.8	29.0	38.4	30.6*	40.4	39.2	45.5
S.E. 1.3	1.2	2.9	1.6	2.2	2.6	4.1	4.5	3.5	2.6	2.9	4.2

* $p<0,05$ Tourniquet (T) vs control (c) limbs.
** $p<0,01$ Tourniquet (T) vs control (c) limbs.

FIGURE 4.2

MUSCLE PHOSPHOFRUCTOKINASE ACTIVITY (μmol min^{-1} g^{-1} wet weight) IN RAT GASTROCNEMIUS MUSCLE AT VARIOUS TIMES AFTER ONE HOUR OF TOURNIQUET ISCHAEMIA.



NOTE THAT EACH POINT REPRESENTS THE MEAN ± S.E. FOR SIX MEASUREMENTS.

TABLE 4.3

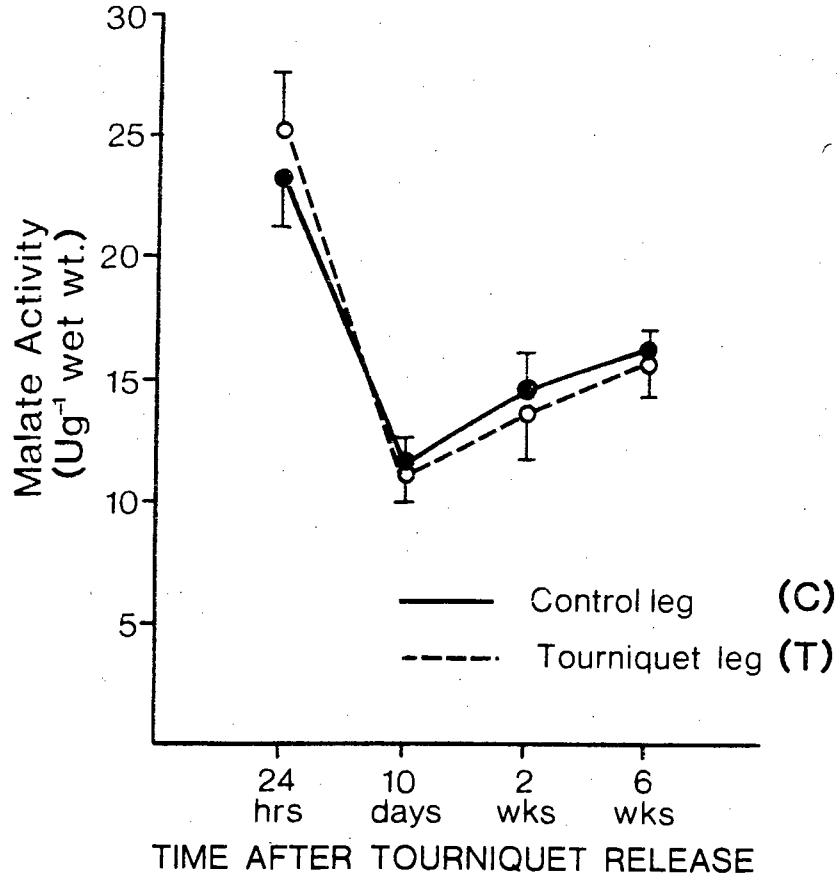
MUSCLE MALATE DEHYDROGENASE ACTIVITY (U g^{-1} wet weight) IN RAT GASTROCNEMIUS MUSCLE AT VARIOUS TIMES AFTER ONE HOUR OF TOURNIQUET-INDUCED ISCHAEMIA.

	TIME AFTER TOURNIQUET RELEASE							
	24 HOURS		10 DAYS		2 WEEKS		6 WEEKS	
	T	C	T	C	T	C	T	C
	21.7	22.8	9.2	10.7	9.4	9.8	13.0	16.3
	29.9	27.1	10.1	11.6	12.0	14.0	19.5	17.4
	28.2	19.5	10.9	8.4	11.5	14.5	12.1	15.7
	20.3	25.0	8.3	15.9	17.3	16.7	13.4	14.6
	19.2	15.4	17.7	10.8	10.2	15.0	21.3	18.2
	31.5	28.8	11.5	10.6	21.3	19.1	15.3	14.5
MEAN	25.1	23.1	11.3	11.3	13.6	14.8	15.8	16.1
S.E.	2.2	2.9	1.4	1.0	1.9	1.3	1.5	0.6

Note that there were no significant differences in MDH activities in the muscles of tourniquet (T) and control (C) leg at any time after the tourniquet was released.

FIGURE 4.3

MUSCLE MALATE DEHYDROGENASE ACTIVITY (Ug^{-1} wet wt) IN THE RAT GASTROCNEMIUS AT VARIOUS TIMES AFTER ONE HOUR OF TOURNIQUET ISCHAEMIA.



EACH POINT REPRESENTS THE MEAN ± S.E. FOR SIX MEASUREMENTS.

There were no significant differences in the muscle MDH activities between the tourniquet and control legs, at any of the time periods measured. For this reason no additional measurements were made after 6 weeks.

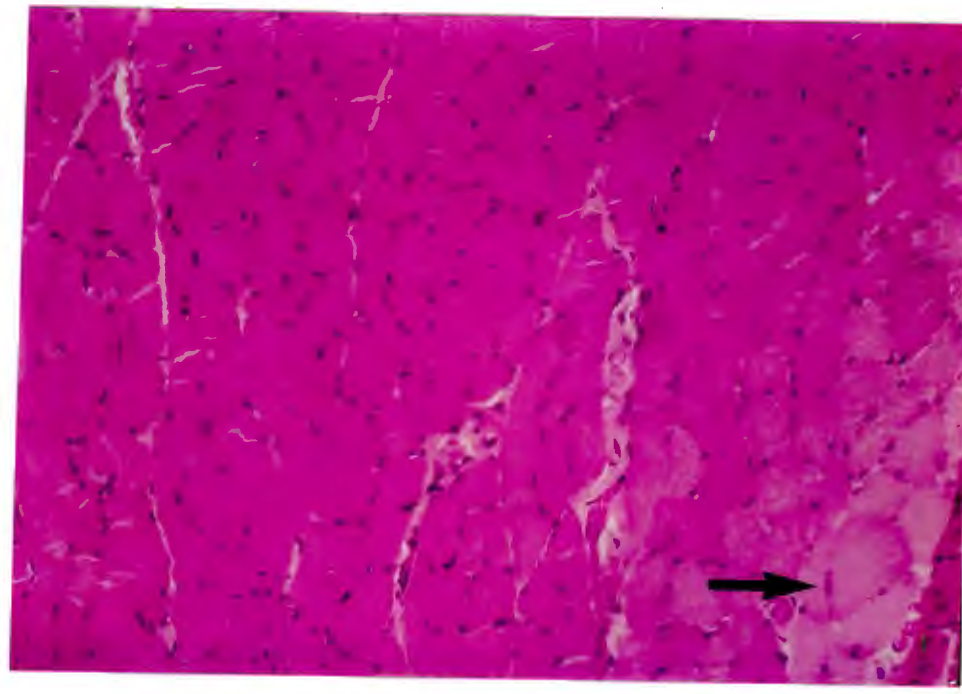
The reason for the fall in MDH activity in both the tourniquet and control legs is unclear but could be due to decreased levels of activity in the rats after the tourniquet application.

1.2 Histological changes.

Twenty four hours after the tourniquet was released, the only features found were those of an increase in the interstitial cellular material and signs of early degeneration such as enlarged fibres with a faint cytoplasm (Fig. 4.4a compared to Fig. 4.4b which is the control sample from the unaffected leg of the same rat. It is of interest that some histological samples from tissue examined 24 hours after the tourniquet was released, appeared normal.

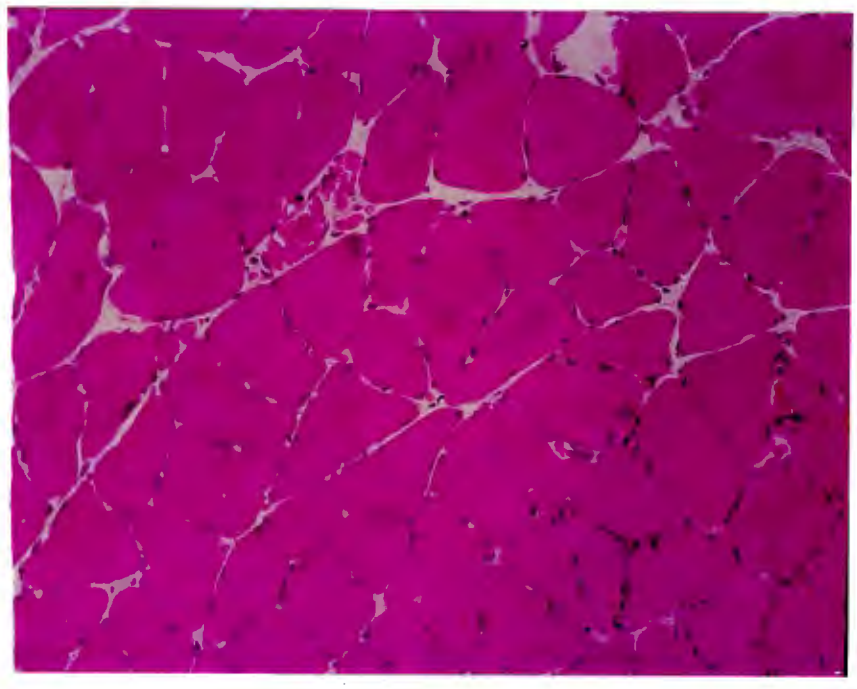
In common with the biochemical changes, the histological appearance of the muscle deteriorated with time after tourniquet release, and all the samples taken ten days after tourniquet released showed gross signs of cellular degeneration and necrosis (Fig. 4.5a compared to Fig. 4.5b which is the control sample taken from the unaffected leg of the same rat).

FIGURE 4.4a



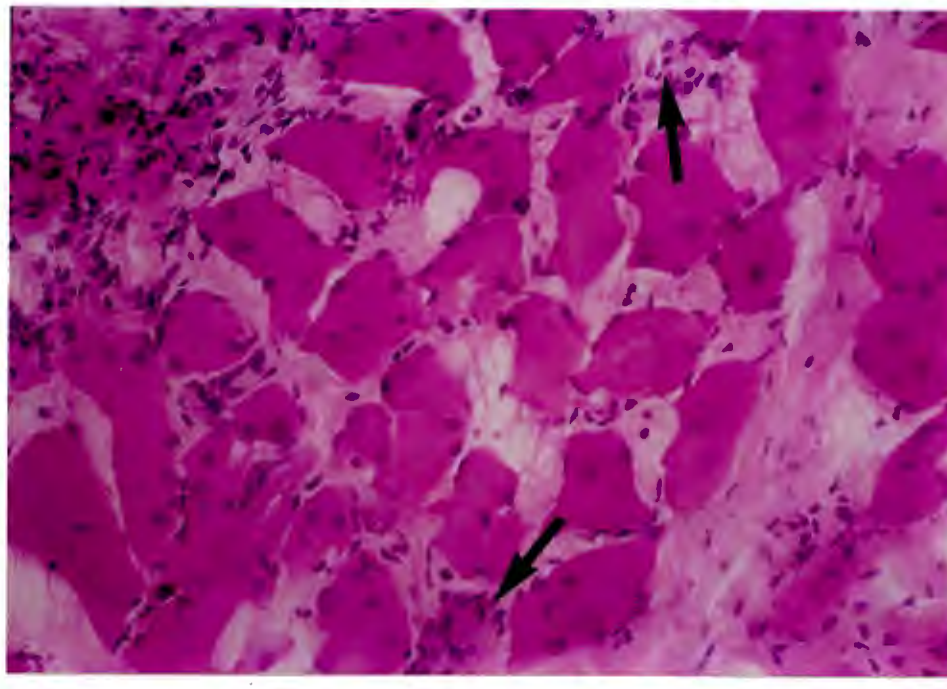
LEGEND TO FIGURE: Histological section of rat gastrocnemius muscle sampled 24 hours after one hour of tourniquet ischaemia. There is an increase in interstitial cellular material and a few muscle cells (arrowed) are undergoing the initial stages of degeneration as indicated by the arrow. (H and E X200).

FIGURE 4.4b



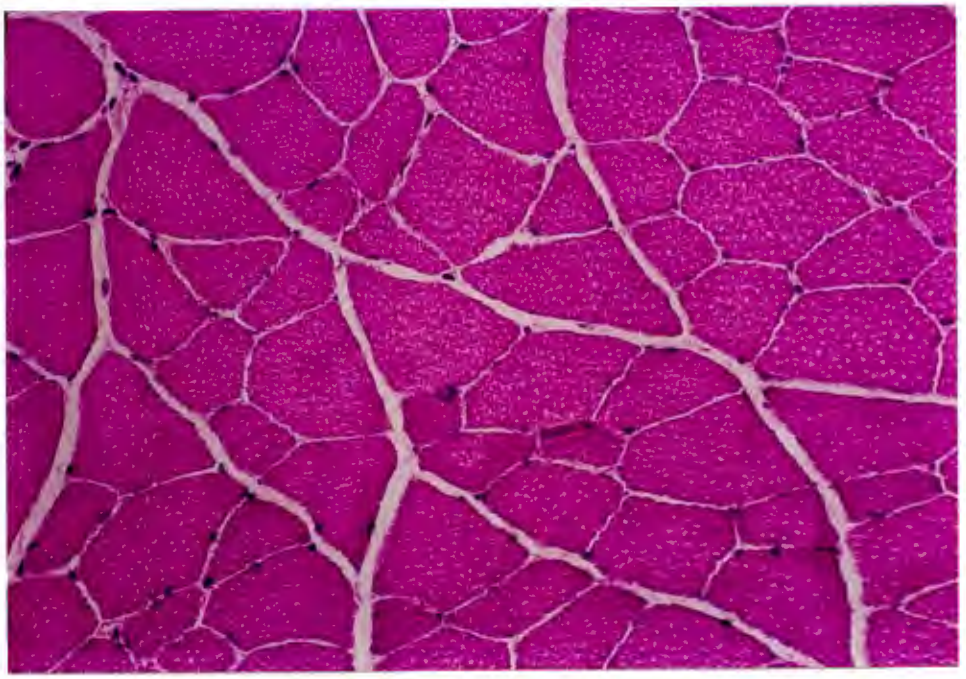
LEGEND TO FIGURE: Control histological section taken from the unaffected leg of the rat studied in Figure 4.4a (H and E X400).

FIGURE 4.5a



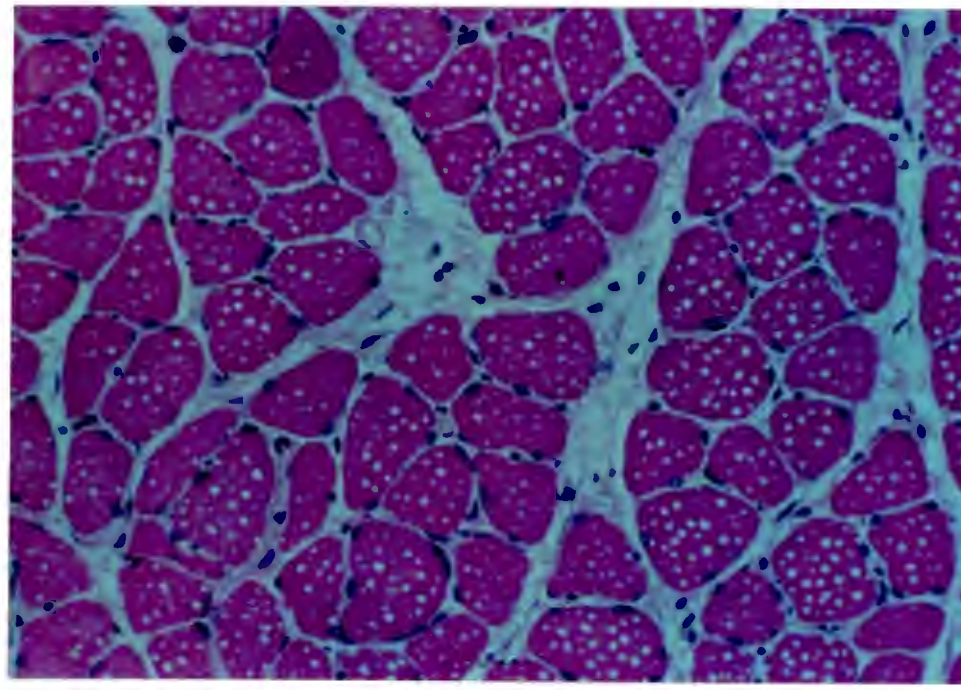
LEGEND TO FIGURE: Histological section of rat gastrocnemius muscle sampled 10 days after one hour of tourniquet ischaemia. There are marked inflammatory changes. Degenerated muscle cells being phagocytozed by macrophages are also present (arrows). (H and E X400).

FIGURE 4.5b



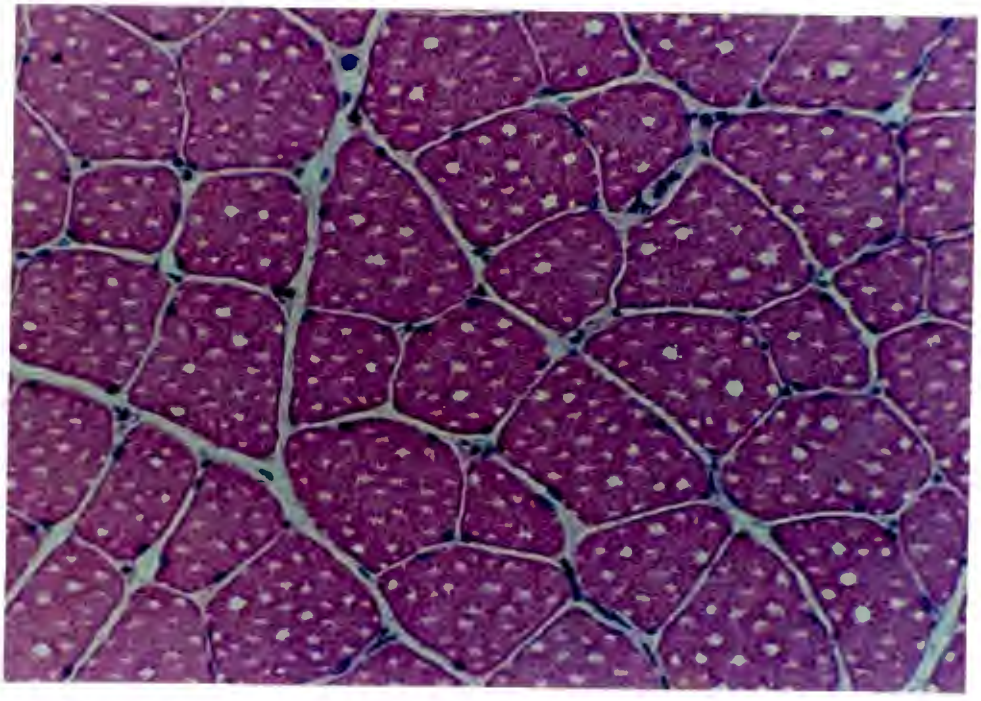
LEGEND TO FIGURE: Control histological section taken from the unaffected leg of the rat studied in Figure 4.5a. (H and E X400).

FIGURE 4.6a



LEGEND TO FIGURE: Histological section of rat gastrocnemius muscle sampled 2 weeks after one hour of tourniquet ischaemia. Regenerating muscle cells are present. Note the abundant nuclei and different cell sizes compared to the control sample of Fig. 4.6b. (H and E X400).

FIGURE 4.6b

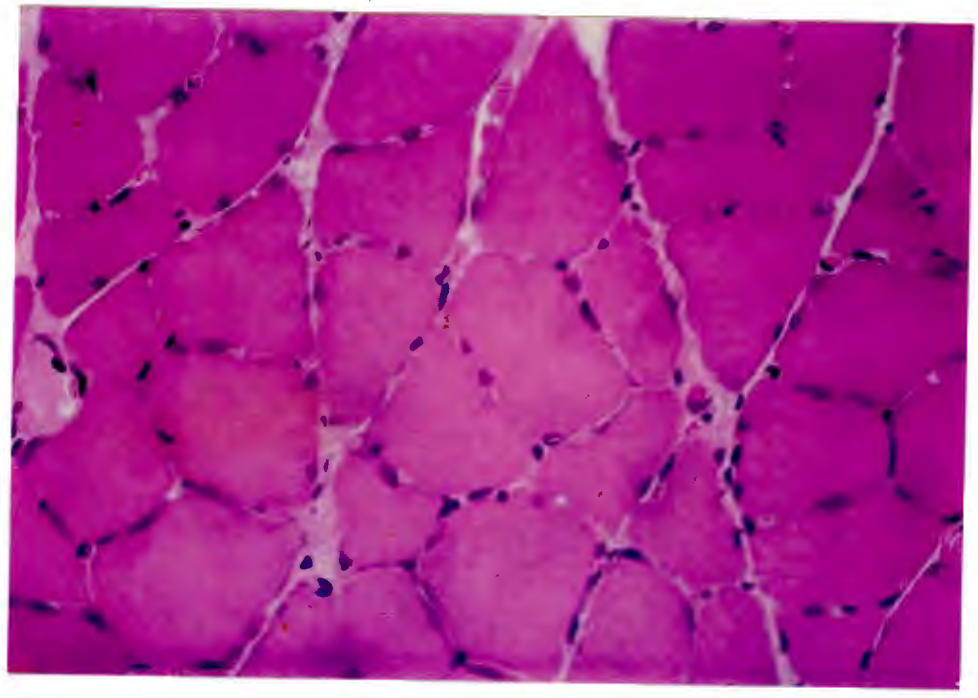


LEGEND TO FIGURE: Control histological section taken from the unaffected leg of the rat studied in Figure 4.6a. (H and E X400).

Two weeks after the release of the tourniquet, the major histological feature was that of muscle cell regeneration. This was shown by the presence of small muscle cells with prominent nuclei. There was also marked intercellular fibrosis and oedema (Fig. 4.6a compared to Fig. 4.6b which is the control sample from the unaffected leg of the same rat). Six weeks after tourniquet release, the muscle cells of the involved limb had matured. However the nuclei were prominent and not as peripherally stiuated as were those in the control samples (Compare Figs. 4.7a and 4.7b).

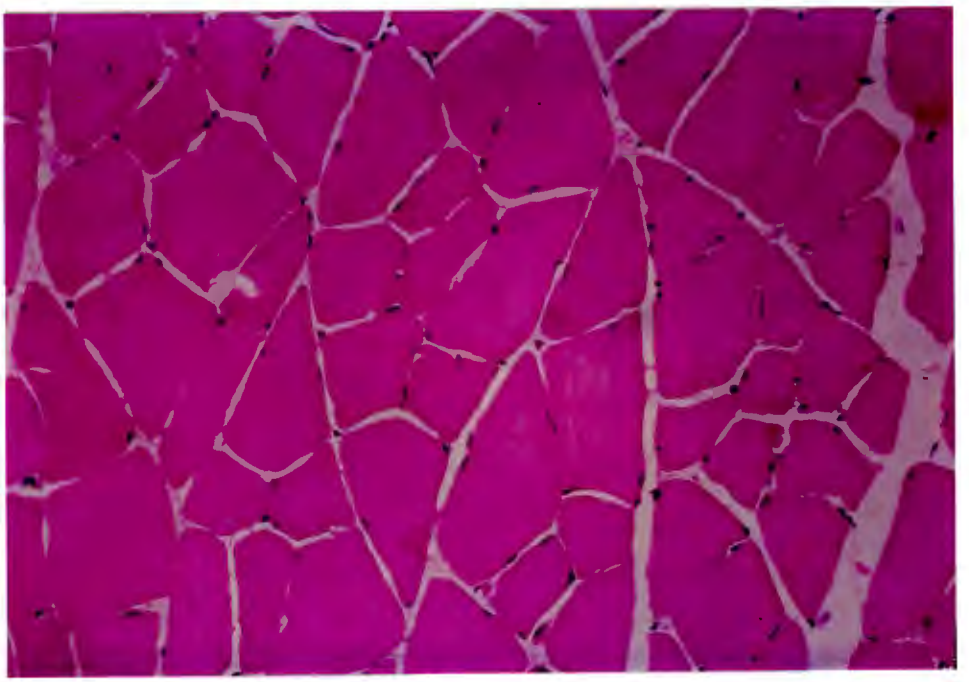
Three months after the tourniquet was released all histological sections appeared normal when compared to the sections from the unaffected limb muscles (Fig. 4.8).

FIGURE 4.7a



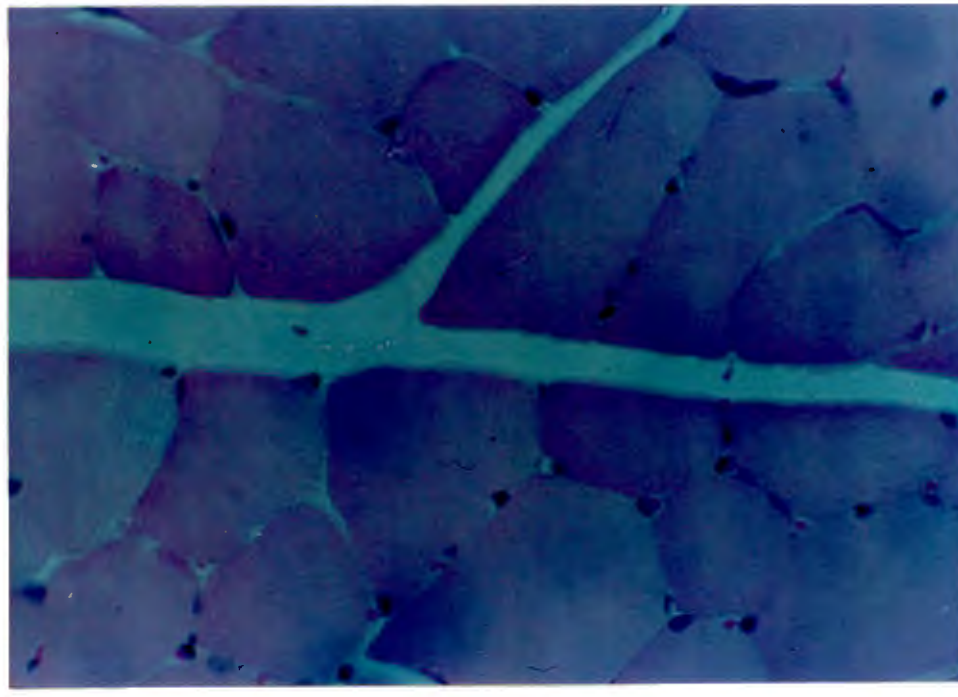
LEGEND TO FIGURE: Histological section of rat gastrocnemius muscle samples 6 weeks after one hour of tourniquet ischaemia. The presence of maturing regenerated muscle cells is indicated by an increase in the number of nuclei which have not fully migrated towards the periphery of the cell. (H and E X400).

FIGURE 4.7b



LEGEND TO FIGURE: Control histological section taken from the unaffected leg of the rat studied in Figure 4.7a. (H and E X400).

FIGURE 4.8



LEGEND TO FIGURE: Histological section of rat gastrocnemius muscle sampled 3 months after one hour of tourniquet ischaemia showing a normal histological appearance (H and E X400).

2. THE BIOCHEMICAL AND FUNCTIONAL CHANGES IN THE QUADRICEPS MUSCLE OF POST MENISECTOMY PATIENTS SIX WEEKS AFTER SURGERY.

2.1 Biochemical Changes.

(a) Muscle glycogen levels.

Table 4.4 lists the muscle glycogen levels of the vastus lateralis muscles of six post-menisectomy patients, six weeks after surgery. These patients had received no post-surgery rehabilitation. The corresponding mean values (±S.E.) are shown in Figure 4.9. The muscle glycogen levels were significantly lower in the vastus lateralis muscle of the operated leg compared to the control leg.

Table 4.5 lists the muscle glycogen levels in the vastus lateralis muscles of two patients that had undergone an isokinetic exercise rehabilitation programme. There was no difference in muscle glycogen levels in the vastus lateralis muscle of the operated and control legs.

2.2 Muscle strength Changes.

Table 4.6 list the peak knee extension torques at testing speeds of $60°sec^{-1}$ and $240°sec^{-1}$ in the same six post-menisectomy patients when measured six weeks after surgery. The mean resultant torque developed in the quadriceps muscle of the operated leg was significantly lower ($p<0.05$) than the non-operated leg at both testing speeds. Table 4.7 lists the

TABLE 4.4

(μmol glucosyl units g^{-1} wet weight) MUSCLE GLYCOGEN LEVEL IN THE VASTUS LATERALIS MUSCLES OF OPERATED AND NON-OPERATED LEGS OF SIX POST-MENISECTOMY PATIENTS SIX WEEKS AFTER SURGERY.

SUBJECT	OPERATED LEG	NON-OPERATED LEG
S.S.	65.6	116.7
D.H.	24.6	70.8
M.W.	43.9	86.5
J.B.	77.3	119.6
A.L.	74.3	121.2
D.A.	130.3	160.9
MEAN	69.3*	112.6
S.E.	14.7	12.8

$p<0,05$ compared to non-operated leg.

FIGURE 4.9

MUSCLE GLYCOGEN LEVELS (μmol glucosyl units g^{-1} wet weight) IN THE VASTUS LATERALIS MUSCLES OF OPERATED AND NON-OPERATED LEGS OF SIX POST-MENISECTOMY PATIENTS SIX WEEKS AFTER SURGERY.

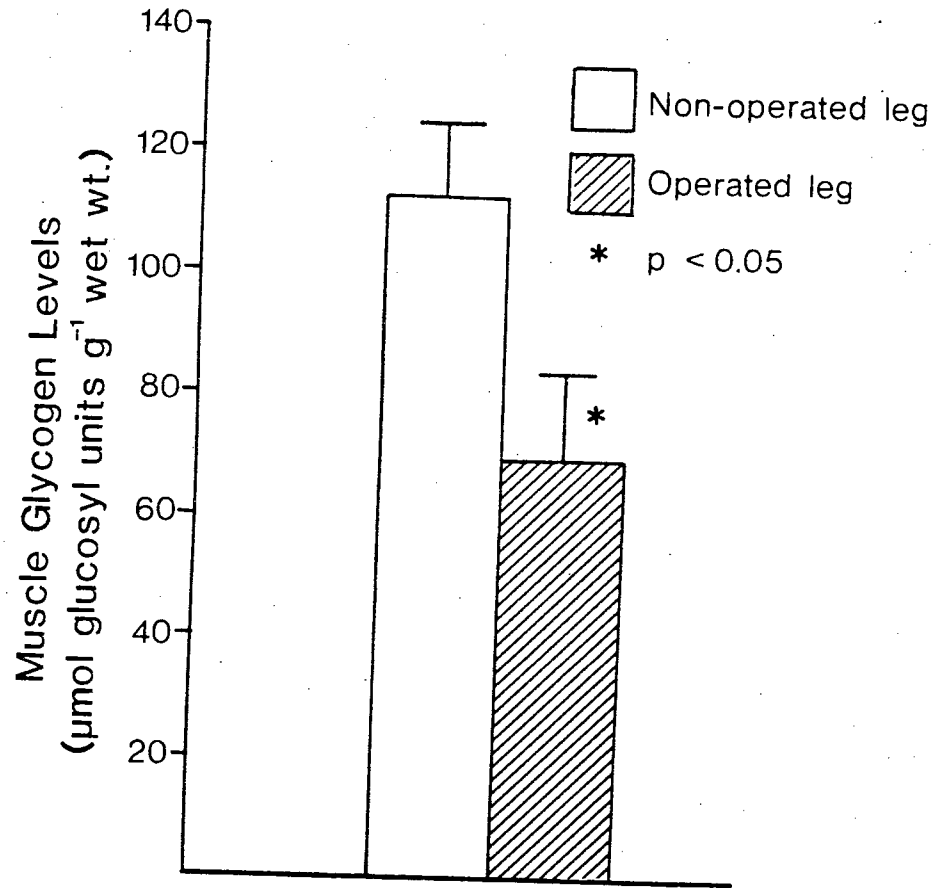


TABLE 4.5

MUSCLE GLYCOGEN (μmol glucosyl units g^{-1} wet weight) LEVELS IN THE VASTUS LATERALIS MUSCLE OF OPERATED AND NON-OPERATED LEGS OF TWO POST-MENISECTOMY PATIENTS WHO HAD UNDERGONE AN ISOKINETIC EXERCISE REHABILITATION PROGRAMME.

SUBJECT	OPERATED LEG	NON-OPERATED LEG
J.G.	129,1	124,4
Sv.G	95,0	104,0
MEAN	112	114

TABLE 4.6

PEAK TORQUES (Nm) OF KNEE FLEXION (F) AND KNEE EXTENSION (E) IN OPERATED AND NON-OPERATED LEGS AT TESTING SPEEDS OF 60° SEC^{-1} AND 240° SEC^{-1} IN SIX POST-MENISECTOMY PATIENTS SIX WEEKS AFTER SURGERY.

	60° SEC^{-1}				240° SEC^{-1}			
SUBJECT	OPERATED LEG		NON-OPERATED LEG		OPERATED LEG		NON-OPERATED LEG	
	F	E	F	E	F	E	F	E
S.S.	155	152	172	244	105	95	89	135
D.H.	191	272	197	326	98	126	103	147
M.W.	124	190	148	251	112	108	93	142
J.B.	180	234	201	343	118	109	121	151
A.L.	175	225	218	324	145	160	140	200
D.A.	140	162	170	216	42	65	58	79
MEAN	161	206*	184	284	103	110*	101	142
S.E.	9.6	17.2	9.5	19.8	12.7	11.8	10.5	14.4

* Values are expressed as Nm.

* $p<0,05$ operated leg vs. non-operated leg.

TABLE 4.7

PEAK TORQUES (Nm) OF KNEE FLEXION (F) AND KNEE EXTENSION (E) IN OPERATED AND NON-OPERATED LEGS AT TESTING SPEEDS OF 60° SEC^{-1} AND 240° SEC^{-1} IN SIX POST-MENISECTOMY PATIENTS SIX WEEKS AFTER SURGERY.

	60° SEC^{-1}		240° SEC^{-1}	
SUBJECT	OPERATED LEG	NON-OPERATED LEG	OPERATED LEG	NON-OPERATED LEG
J.G.	167	169	95	95
Sv.G	217	204	115	117
MEAN	192	187	105	106

Values are expressed as Nm.

peak knee extension torque at testing speeds of $60°sec^{-1}$ and $240°sec^{-1}$ in the two patients who had undergone an isokinetic exercise rehabilitation programme. Although the sample size is too small to be of statistical significance, it is of interest that peak torques developed by the quadriceps muscles of the operated and non-operated legs were not different.

It should also be noted that peak flexion torque produced by the hamstring muscles was not different between the operated and non-operated legs of any of these subjects, indicating that post tourniquet muscle weakness is specific to the quadriceps muscles.

3. AN ELECTROMYOGRAPHIC STUDY OF POST-MENISECTOMY PATIENTS.

The EMG study of the vastus medialis muscle of 12 post-menisectomy patients revealed no signs of nerve damage using the following criteria for nerve damage: spontaneous activity at rest and the presence of sharp positive waves, fibrillation potentials and an increase in the number of polyphasic motor-unit potentials greater than 30%.

The patients were examined on average 7,4 weeks after surgery with a range of 4-12 weeks.

4. THE EFFECTS OF THREE DIFFERENT EXERCISE REHABILITATION PROGRAMMES ON QUADRICEPS MUSCLE STRENGTH OF POST-MENISECTOMY PATIENTS SIX WEEKS AFTER SURGERY.

Table 4.8 lists the peak knee flexion and knee extension torques at testing speeds of 60° sec^{-1} and 240° sec^{-1} in three groups of post-menisectomy patients six weeks after surgery. Group I (n=5) received no exercise rehabilitation, Group II (n=5) underwent a routine post-menisectomy rehabilitation programme and Group III participated in an isokinetic rehabilitation programme. The corresponding mean (±S.E.) values are depicted in figures 4.10 - 4.13.

At a testing speed of 60°sec^{-1} the peak torques of knee extension were significantly lower ($p<0.05$) when compared to the non-operated legs in both groups I and II (Fig. 4.10). However, there were no significant differences between the strengths of knee extensors of the operated leg compared to the non-operated leg in the Group III patients (Fig. 4.10).

At a testing speed of 240°sec^{-1} the peak torques of knee extension were significantly lower ($p<0.05$) in the operated leg compared to the non-operated leg of patients in Group II. There were no significant differences in the peak torques of knee extension of the operated leg compared to the non-operated leg in Groups I and III (Fig. 4.11). There were no significant differences in the peak torques of knee flexion of the operated leg when compared to the non-operated leg in any of the three groups of patients at both testing speeds (Figs. 4.12 and 4.13).

TABLE 4.8

PEAK TORQUES (Nm) OF KNEE FLEXION (F) AND KNEE EXTENSION (E) IN OPERATED AND NON-OPERATED LEGS AT TESTING SPEEDS OF 60° SEC^{-1} AND 240° SEC^{-1} IN SIX POST-MENISECTOMY PATIENTS SIX WEEKS AFTER SURGERY.

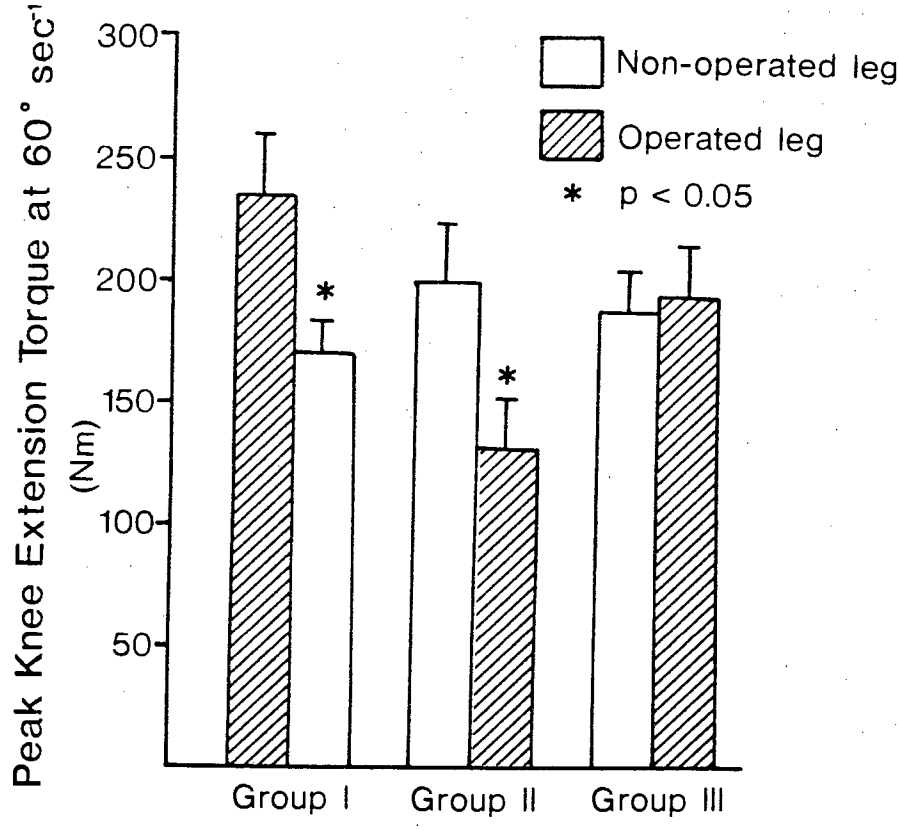
GROUP I - NO REHABILITATION

	60° SEC^{-1}				240° SEC^{-1}			
SUBJECT	OPERATED LEG		NON-OPERATED LEG		OPERATED LEG		NON-OPERATED LEG	
	F	E	F	E	F	E	F	E
A.A.	97	150	115	211	58	97	61	112
S.S.	155	152	172	244	105	95	89	135
K.L.	54	108	108	197	34	34	40	95
J.S.	177	252	177	306	165	140	155	170
J.R.	122	190	148	218	114	144	91	138
MEAN	121	170*	133	235	95,2	102	87,2	130
S.E.	21,6	24,2	14,2	19,3	22,9	19,9	19,4	12,7
GROUP II - ROUTINE REHABILITATION								
H.N.	82	104	130	215	37	56	52	84
D.G	116	196	174	244	51	100	69	117
A.R.	105	139	101	191	56	67	40	84
P.T.	109	142	109	225	55	80	55	109
D.L.	35	78	65	119	31	61	27	56
MEAN	89,4	131,8*	115,8	198,8	46	72,8*	48,6	40,2
GROUP III - ISOKINETIC REHABILITATION								
J.G.	118	187	114	189	72	95	78	95
SvG.	170	217	156	204	126	115	119	117
D.S.	87	108	100	141	51	73	49	74
G.G.	141	282	151	202	81	127	112	117
E.G.	184	197	174	225	146	154	138	146
MEAN	140	194	139	188	95	114	99	110
S.E.	17,5	28,6	13,8	14,8	17,6	13,5	15,9	12,1

*Denotes operated leg is significantly ($p<0.05$) weaker compared to non-operated leg.

FIGURE 4.10

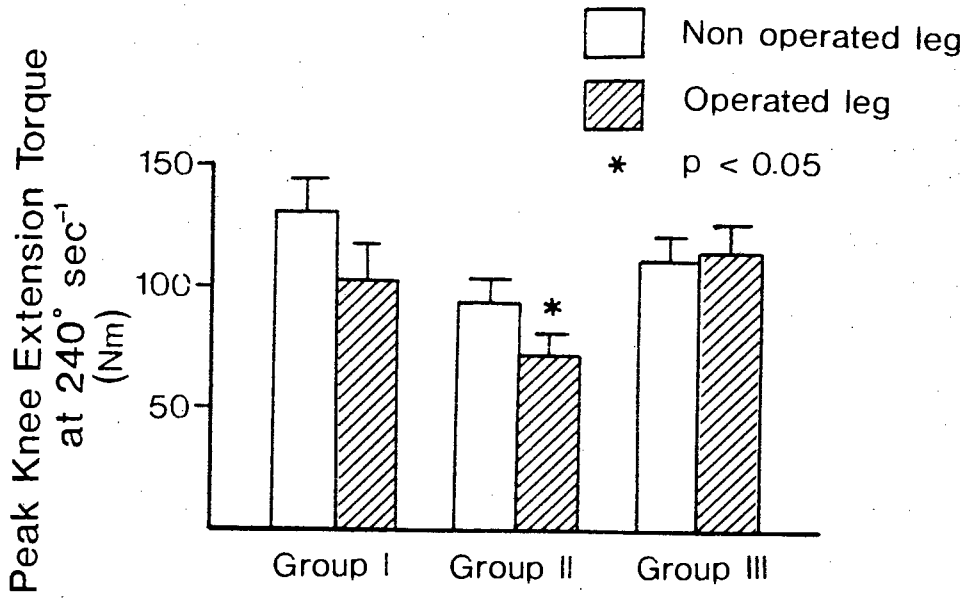
PEAK TORQUES (Nm) OF KNEE EXTENSION AT A TESTING SPEED OF 60° SEC^{-1} IN THREE GROUPS OF POST-MENISECTOMY PATIENTS SIX WEEKS AFTER SURGERY.



Key: Group I (n=5) underwent no rehabilitation; Group II (n=5) had routine post-menisectomy rehabilitation and Group III (n=5) participated in an isokinetic exercise rehabilitation programme.

FIGURE 4.11

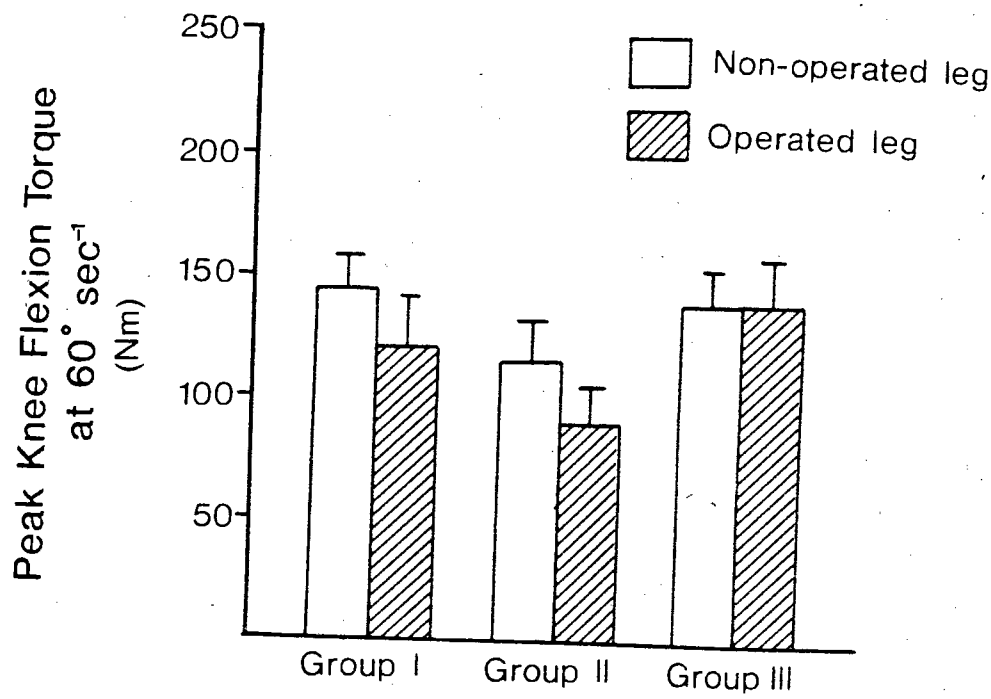
PEAK TORQUES (Nm) OF KNEE EXTENSION AT A TESTING SPEED OF 240° SEC^{-1} IN THREE GROUPS OF POST-MENISECTOMY PATIENTS SIX WEEKS AFTER SURGERY.



Key: Group I (n=5) underwent no rehabilitation; Group II (n=5) had routine post-menisectomy rehabilitation and Group III (n=5) participated in an isokinetic exercise rehabilitation programme.

FIGURE 4.12

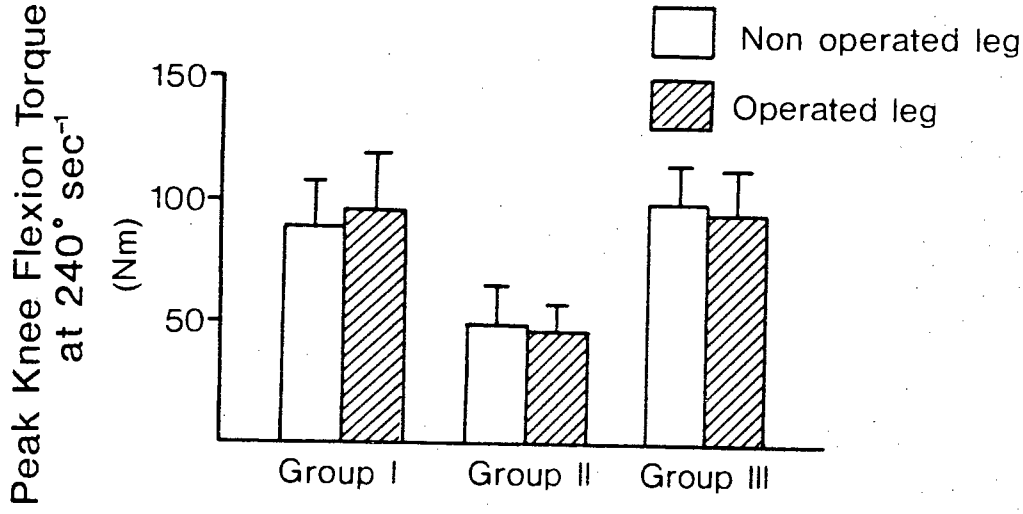
PEAK TORQUES (Nm) OF KNEE FLEXION AT A TESTING SPEED OF 60° SEC^{-1} IN THREE GROUPS OF POST-MENISECTOMY PATIENTS SIX WEEKS AFTER SURGERY.



Key: Group I (n=5) underwent no rehabilitation; Group II (n=5) had routine post-menisectomy rehabilitation and Group III (n=5) participated in an isokinetic exercise rehabilitation programme.

FIGURE 4.13

PEAK TORQUES (Nm) OF KNEE FLEXION AT A TESTING SPEED OF 240° SEC^{-1} IN THREE GROUPS OF POST-MENISECTOMY PATIENTS, SIX WEEKS AFTER SURGERY.



Key: Group I (n=5) underwent no rehabilitation; Group II (n=5) had routine post-menisectomy rehabilitation and Group III (n=5) participated in an isokinetic exercise rehabilitation programme.

CHAPTER V

DISCUSSION OF THE RESULTS

1. THE BIOCHEMICAL AND HISTOLOGICAL CHANGES IN RAT HINDLIMB MUSCLE FOLLOWING ONE HOUR OF TOURNIQUET ISCHAEMIA AND THE TIME COURSE OF RECOVERY.

1.1 Biochemical changes.

There were significant biochemical changes after one hour of tourniquet ischaemia in rat hindlimb muscle.

The ability of the muscle to store glycogen was significantly impaired 24 hours after the ischaemic bout. The muscle glycogen levels in the tourniquet leg then fell further from 10 to 14 days after the tourniquet had been released (Fig. 4.1). Muscle glycogen levels returned gradually to normal but reached control levels only three months after tourniquet release.

During tourniquet ischaemia, the muscle is truly anoxic and therefore totally reliant on oxygen-independent processes in particular glycogenolysis to provide energy. Low muscle glycogen levels and correspondingly high muscle or blood lactate levels during and immediately after tourniquet ischaemia are therefore to be expected (Hepenstall et al 1979, Haljamae and Enger 1975, Larsson and Hultman 1979 and Stock et al 1971).

This study confirms the findings of Stock et al (1971) and show that muscle glycogen levels remain low for at least 6 weeks after

tourniquet release, indicating marked and sustained cellular damage. Using histochemical stains, Snow (1973) also demonstrated the absence of glycogen in degenerating rat muscle tissue and found that glycogen could be demonstrated histochemically only in the latter stages of muscle cell regeneration. Similarly, Scully et al (1961) showed an absence of glycogen in ischaemically-induced necrosis of muscle fibres in dogs.

Phosphofructokinase, a rate limiting enzyme in the glycolytic pathway, followed a closely similar pattern and was markedly lower in the tourniquet leg compared to the control leg 24 hours after tourniquet release (Fig 4.2). Between 10 and 14 days after tourniquet release PFK activity decreased even further, whereafter it gradually recovered. Three months after the ischaemic insult, the PFK activity of the muscle of the tourniquet leg was slightly but insignificantly lower than the control. Smith (1965) has also shown reduced glycolytic capacity following muscle necrosis.

The activity of glucose 6-phosphate dehydrogenase, which is low in normal skeletal muscle, increases during muscle cell regeneration (Wagner et al 1977). Glucose 6-phosphate dehydrogenase diverts glucose 6-phosphate from glycolysis to the hexose-monophosphate shunt. This shunt generates the hexoses necessary for RNA synthesis which are essential during muscle cell regeneration. A need for diversion of carbon from glycolysis to the hexose monophosphate shunt could explain the prolonged loss of PFK activity in regenerating muscle shown in this study.

There were no differences in the activity of malate dehydrogenase (MDH), a citric acid cycle intermediate, between the tourniquet leg and the unaffected leg after tourniquet ischaemia (Fig. 4.3). The fall in MDH activity in the muscles of both the control and tourniquet limbs suggests that the animals became less active after the tourniquet application, probably because of muscle damage in their one limb.

Histochemical studies of degenerating muscle cells have measured succinate dehydrogenase (SDH), also a citric acid cycle enzyme. These studies have shown a comparatively high SDH activity during muscle cell degeneration (Dahlback 1970, Smith 1965 and Snow 1973). Moore (1956) in a similar study to this one, showed that despite marked signs of cellular degeneration, SDH activity was essentially unaffected. Scully et al (1961) concluded that it was not possible to distinguish normal and abnormal muscle on the basis of SDH staining intensity, even after 48 hours of ischaemia. Others (Dahlback, 1970; Carlson, 1983) have demonstrated a lower oxidative capacity, as measured by SDH activity in regenerating muscle.

1.2 Histological changes.

There were marked histological changes following tourniquet application.

Twenty four hours after tourniquet release, there were already signs of early muscle cell degeneration and by ten days there was evidence of gross cellular degeneration and

necrosis (Fig. 4.5a). Muscle regeneration was evident six weeks after tourniquet release and the muscle was again histologically normal, after three months after tourniquet release.

The study therefore confirms the work of Dahlback (1970) who showed that after tourniquet ischaemia the histological changes become worse with time. He also showed that the most severe histological changes occurred only 10-15 days after tourniquet release. It is therefore clear that the majority of studies of the histological changes induced by the tourniquet have underestimated the true extent of the damage because they have not followed changes for a sufficient period of time.

2. THE BIOCHEMICAL AND FUNCTIONAL CHANGES IN THE QUADRICEPS MUSCLE OF POST-MENISECTOMY PATIENTS SIX WEEKS AFTER SURGERY.

The most remarkable finding in this group of subjects who had undergone menisectomy was the markedly lower glycogen levels in the quadriceps muscle of the operated leg compared to the non-operated leg (Fig. 4.9). No similar finding could be found in the literature, it seems likely that prolonged impairment of muscle glycogen storage capacity may be indicative of cellular degeneration and regeneration (Snow, 1973). However, Macdougall et al (1977) have also shown a 40% decrease in the glycogen storage capacity of the triceps muscles subjected to 5 weeks of cast immobilization. But it is unlikely that immobilization-induced cellular damage was an important factor in this study. Thus decreased muscle glycogen levels occurred even in a patient A.L. who underwent a partial arthroscopic menisectomy. This patient was weight bearing the day after surgery. Furthermore, the majority of the other patients had resumed normal recreational activities at the time of the biopsy.

Another possibility is that the low muscle glycogen levels were present before surgery as most of the patients had a history of knee injury preceeding the actual surgical procedure. However Karumo et al (1977) have shown marked atrophy of both type I and type II muscle fibres 4 weeks after surgery when compared to the histological appearance of muscle samples taken prior to surgery. He concluded that these marked changes were a result of the surgery and not of the initial injury.

That this biochemical change was not merely an incidental laboratory finding is shown by the correlation between low muscle glycogen levels and significant strength deficits in the operated legs (Table 4.6). Interesting, 2 subjects who were effectively rehabilitated not only showed no differences in muscle glycogen levels between the operated and non-operated legs, but also had equal strengths in both legs.

Whether these changes are directly due to the tourniquet ischaemia is obviously not resolved, but it seems likely in view of our animal studies. Other factors that may cause muscle weakness after surgery include disuse and immobilization or both (Booth 1982) but this seems an unlikely cause in these subjects most of whom had already begun to resume recreational or sporting activity at the time of the biopsy, six weeks after surgery.

Pain and joint effusion may also play a significant role in causing post-surgical atrophy. De Andrade et al (1965) showed that joint capsule effusion can directly inhibit alpha motor neurones at the level of the spinal cord. Pain is also known to illicit reflex muscular inhibition. However, Young et al (1983) injected an analgesic into groups of post-operative menisectomy patients and used electromyography to compare muscle inhibition with that found in a control group who did not receive analgesia. They showed that although post-menisectomy subjects in the analgesia group had no pain they nevertheless demonstrated marked inhibition of the quadriceps muscle contraction. The authors concluded that quadriceps inhibition after menisectomy is not simply due to pain, further

suggesting that muscle or nerve damage or both, may be involved.

An important practical point highlighted by this study is that many patients may be returning to sport after menisectomy with both marked biochemical abnormalities and functional weakness of the quadriceps muscle. The implications of this finding with regard to post-operative sporting performance, and the risks of re-injury and the development of long term degenerative joint changes needs to be further investigated. The occurrence of re-injury which is known to be high in post-menisectomy patients Sonneholm et al (1981) may also be a manifestation of the early post-operative changes demonstrated in this study.

3. AN ELECTROMYOGRAPHIC STUDY OF POST-MENISECTOMY PATIENTS.

In this study there were no signs of tourniquet-induced nerve damage in the vastus medialis muscles of 12 post-menisectomy patients. As these results are in conflict with the findings of previous studies (Dobner and Nitz, 1981; Saunders et al 1979 and Weingarden et al 1979), the aim of this discussion will be to reconcile what appear to be conflicting data.

From the outset it must be stressed that these electromyographic data were obtained on 12 subjects, 11 of whom showed decreases in the muscle strength of the operated leg compared to the non-operated leg. Furthermore, a number of subjects whose muscle biopsies demonstrated biochemical abnormalities were also included in this study. In other words the majority of the muscles tested were functionally impaired and some also showed biochemical abnormalities.

One possibility is that either different tourniquet pressures used during surgery or the duration of tourniquet exposure, may explain differences between the studies. Casual enquiries made to some of the surgeons who treated our subjects showed that these surgeons used tourniquet pressures that fell between 350-500 mmHg as also used in the studies of Dobner and Nitz (1982), Saunders et al (1979) and Weingarden et al (1979). Very short tourniquet times was also not likely to be a factor as the study of Saunders et al (1979) found that 22% of the subjects demonstrated EMG abnormalities after tourniquet times of less than 15 minutes. Moreover one

patient in the study of Dobner and Nitz (1982) demonstrated EMG abnormalities after a tourniquet that lasted only 8 minutes. Thus EMG abnormalities have been reported even after very short tourniquet times and it is unlikely that the surgical procedures in our subjects were of even such short duration.

The delay after surgery before the subjects were examined may have had an important bearing on the results. In the studies of Weingarden et al (1979) and Saunders et al (1979), all patients were examined 3-4 weeks after surgery. The average duration of symptoms antedating surgery in these studies was 50,9 days with a range of 27 days to 5 months. Dobner and Nitz (1982) examined patients 6 weeks after surgery.

In this study subjects were examined an average of 7,25 weeks after surgery, with a range of 4 to 12 weeks. Thus a number of patients examined in this study may have had EMG abnormalities which had resolved by the time of examination.

Another factor in the failure of this study to demonstrate any EMG abnormalities is the anatomical site investigated. Saunders et al (1979) reported 6 subjects who demonstrated EMG abnormalities in 2 or 3 heads of the quadriceps muscle, rather than in all 4 heads. In this study only the vastus medialis was examined. Moreover, Dobner and Nitz (1982) showed that the posterior tibial nerve was more commonly affected than the femoral nerve. Interestingly 7 of

of their subjects demonstrated EMG abnormalities only in the tibialis posterior and gastrocnemius muscles.

In summary, the failure of this study to demonstrate tourniquet induced EMG changes 7 weeks after surgery in subjects the majority of whom had functional muscle weakness, indicates that impaired nerve conduction was not the cause of the weakness at the time of examination. Rather it seems likely that muscle cell degeneration of the kind produced in the rat study explains the delayed returned of muscle strength to normal after knee surgery under tourniquet.

4. THE EFFECTS OF REHABILITATION ON QUADRICEPS MUSCLE STRENGTH IN POST-MENISECTOMY PATIENTS, SIX WEEKS AFTER SURGERY.

This study compared the effects of three post-operative rehabilitation programmes for post-menisectomy patients. One group received no formal rehabilitation programme after hospital discharge; the second were subjected to a routine post menisectomy rehabilitation programme, and the third received an intensive isokinetic exercise rehabilitation programme.

The study showed that the strength of the knee extensions in the groups who did not receive isokinetic rehabilitation were significantly impaired when compared to the non-operated leg at a testing speed of $60° \text{ sec}^{-1}$. At a testing speed of $240° \text{ sec}^{-1}$, the strength of the knee extensors were weaker again in both groups, but only significantly so in the group that underwent routine rehabilitation. The strength of the knee flexors was not influenced by either the tourniquet or by rehabilitation.

These results confirm that there is a prolonged delay in the return of knee extension muscle strength after menisectomy in spite of a routine rehabilitation programme, and confirm the findings of previous workers (Campbell and Glenn 1979, Costill et al 1977 and Enslin 1983). Seymour (1969) has also shown that on clinical grounds, there was no difference between post-menisectomy patients who underwent a routine physiotherapy programme and those who did not. He concluded that post-operative physiotherapy was a "waste of time". This study also shows that paitents receiving either no

"routine" or rehabilitation after menisectomy had significantly weaker knee extension compared to the non-operated leg. However this difference disappeared when the subjects performed an intensive isokinetic exericse rehabilitation programme. Thus I conclude routine physiotherapy is a "waste of time" because it is not sufficiently intense and this highlights the urgent necessity for developing effective exercise rehabilitation programmes for post-menisectomy patients.

In a similar study Karumo (1977) showed that an intensive 4-week physiotherapy programme had no effect on the histochemically demonstrated atrophy of the quadriceps muscle compared to pre-operative samples. Thus following a "simple" menisectomy, a 4-week routine post-operative rehabilitation may be inadequate in reversing the induced muscle atrophy but could nevertheless produce normal muscle strength if there was hypertrophy of the viable muscle fibres.

An obvious criticism of the present study is that the strength of the quadriceps of the operated leg may have been impaired before surgery. Very few 'hot' menisectomies are performed and in this study surgery was always performed sometime after the initial injury had occurred. However, in a similar study, Hamberg et al (1983) measured both pre- and post-operative isokinetic strength in operated and control limbs and found a significant strength decrease after surgery suggesting that the muscle weakness is indeed a result of the surgery rather than of the initial injury.

This study also showed that if an effective isokinetic rehabilitation programme is instituted, the strength of the quadriceps muscle is restored within six weeks of surgery. This agrees with the findings of other workers (Sherman et al 1983). As in the study of Grimby et al (1980), the advantages and superiority of isokinetic muscle strength training over isotonic muscle strength training have been practically confirmed.

Urbanova et al (1974) have shown that exercise after surgically-induced ischaemia enhances the rate of recovery of muscle oxidative enzymes. Essentially the same results were shown Van Handel et al (1981) in minced regenerating rat gastrocnemius muscle and by White et al (1981) in autografted rat muscle transplants. There is therefore sufficient data to suggest that the cellular processes of regeneration may be enhanced by exercise.

Another finding of this study was that there were no significant difference in the strengths of the knee flexors of the operated leg compared to the non-operated leg in any of the three rehabilitation groups, at either speed of contraction, a finding that is in agreement with other studies (Arvidsson et al 1981; Duffin, 1977; Hamberg et al 1983; Nicholas et al, 1976; Patel et al, 1982; Prietto et al 1983 and Young et al, 1982). The reason why the hamstrings are not as severely affected as are the quadriceps by knee surgery may be because the femoral nerve is more susceptible than the sciatic nerve to tourniquet induced ischaemia as shown by Dobner and Nitz (1982) and Weingarden et al (1979). Alternatively, the leg is usually immobilised in extension immediately after

surgery, resulting in the knee flexors being relatively stretched and the knee extensors being immobilized in a relatively shortened position. It has been suggested that immobilization in a stretched position may protect the flexors from the effect of the tourniquet (Eriksson, 1981). Thus studies have demonstrated the phenomenon of stretch-induced hypertrophy in both immobilized limbs (Goldspink, 1977) and in denervated muscle (Sola, 1973).

5. SUMMARY AND CONCLUSIONS.

The research described in this thesis was undertaken in order to investigate the cause of quadriceps muscle atrophy after menisectomy, more specifically the possible role of the pneumatic tourniquet in causing this atrophy and the effectiveness of rehabilitation in its reversal.

An initial study of the effect of one hour of tourniquet ischaemia without immobilization and the time course of recovery in rat quadriceps muscle, revealed marked biochemical changes indicative of cellular damage. These included marked decreases in the ability of the affected muscles to store glycogen, and in their PFK activity. MDH activity was unaffected. These changes returned to normal only three months after the ischaemic episode. Histological changes occurred in parallel with these biochemical changes and revelaed evidence of muscle degeneration followed by regeneration. Such changes were not found in the samples from the control leg. As in the biochemical study, damage was most evident approximately 2 weeks after the tourniquet was released. These delayed appearance of damage may result from post-ischaemic changes such as oedema and the "no-reflow" phenomenon which would potentiate the ischaemia. This emphasizes the importance of measuring the delayed effects of tourniquet ischaemia before making recommendations for concerning safety. Alternatively, these delayed changes may be caused by denervation resulting from tourniquet damage to the nerve.

An attempt was made to duplicate these changes in post-menisectomy patients. Muscle glycogen levels were found to be markedly decreased in post-menisectomy patients 6 weeks after surgery.

These subjects also demonstrated significantly impaired quadriceps muscle strength. In contrast, muscle biopsies of 2 subjects who had been effectively rehabilitated showed no differences in either muscle glycogen levels or muscle strength between the operated and non-operated leg.

It is clear that these low muscle glycogen levels coupled with reduced muscle strength, indicate cellular damage. It seems unlikely that disuse was a major factor, as low glycogen levels were shown in one patient who had undergone only a partial arthroscopic menisectomy and most of the other subjects had begun to return to recreational activities.

To determine the possible role of denervation in explaining these findings the EMG study was undertaken. This showed that no EMG abnormalities were present despite residual muscle weakness when the subjects were studied 4-12 weeks after surgery. This could mean that denervation is not a factor explaining the weakness, or that the denervation had resolved.

The effect of rehabilitation on knee muscle strength was studied in 3 groups of post-menisectomy patients 6 weeks after surgery. Only the group receiving an isokinetic exercise programme showed no significant differences in the strengths of the operated and

control quadriceps muscles. No differences in the strengths of the knee flexors were demonstrated in either of the groups.

In conclusion, this study showed that a seemingly "simple" menisectomy is accompanied by marked biochemical and functional changes to the knee extensor muscle group. It seems likely that these changes result from tourniquet-induced ischaemia either to muscle or nerve causing probably muscle cell degeneration of the type found in the rat study. That these changes were significant was shown by the finding that a 6 week routine rehabilitation programme failed to reverse the weakness of the quadriceps muscle. Thus the majority of post-menisectomy patients who receive only routine physiotherapy after surgery are almost certainly returning to sport with inadequately functioning knee extensor muscles. The implications of this in terms of re-injury and long term degenerative osteoarthritis need to be investigated.

In contrast, this study showed that with an effective isokinetic rehabilitation programme, the knee extensor muscle strength was returned to normal within 6 weeks.

6. RECOMMENDATIONS FOR FUTURE RESEARCH.

This study showed that menisectomy is accompanied by marked biochemical changes and functional impairments of knee extensor strength. The evidence that these changes are due to tourniquet-induced ischaemia is persuasive but not conclusive. To fortify the findings of this study, the following recommendations are made. Subjects undergoing knee surgery need to be grouped into distinct categories regarding the length of the tourniquet application - for example, patients undergoing knee surgery lasting less than 30 minutes, to an hour, and more than an hour (as in the case of ligament reconstruction). Furthermore, patients undergoing lower limb surgery such as the pinning and plating of femoral fractures, operations in which tourniquets are not generally used, but which nevertheless result in marked quadriceps muscle atrophy. This atrophy which must be due purely to pain and disuse may be different from ischaemically-induced muscle atrophy. In all these studies, muscle biopsy samples should be performed immediately before and during surgery to establish pre-operative control values. In these studies special emphasis should be placed on histological and biochemical measurements, especially muscle PFK activity which is very resistant to disuse (Haggmark et al 1981). When possible, serial sampling of muscle biopsies should be undertaken to delineate the time course of these post-surgical changes. In addition, muscle glucose-6-phosphate dehydrogenase activity should be measured as this enzyme is not very active in normal skeletal muscle, but seems to be induced during muscle cell regeneration.

On the basis of previous studies (Dobner and Nitz, 1982 and Weingarden et al 1979), it is possible that no EMG changes were demonstrated in this study because these changes had resolved by the time the subjects were examined. It is recommended that similar EMG and nerve conduction studies be undertaken before, and for 6 weeks after surgery.

Finally, the long term effects of these abnormalities need to be determined in terms of the incidence of re-injury, continued athletic performance and the incidence and severity of degenerative osteoarthritic changes in the knee.

APPENDIX I

ANALYTICAL METHODS.

ANALYTICAL METHODS

I Muscle glycogen levels

The weighed muscle sample was macerated with 1 ml KOH (40%) and added to a plastic tube. The tube was placed in a water bath of 100°C for 30 minutes, after which 4 ml of 95% ethanol was added to the solution and the tube was again placed into the water bath for 30 minutes to precipitate the glycogen. The solution was left overnight in the fridge (4°C) and then the supernatant removed after centrifuging (10 minutes at 5000 r.p.m.). One ml 2N HCl was added to the precipitate to hydrolyse the glycogen to glucose and the solution was placed in the water bath at 100°C for 3 hours. 0,2M Tris buffer was added to the solution to bring the pH to 7,5, 200µl of the resultant solution was mixed with 2,8 ml of the reagent mix (see below) and the absorption read at 340 nm (Beckman Spectrophotometer Model 35). The above procedure was carried out over three successive days.

REAGENT MIXTURE

Reagent Mixture	Per Cuvette
Tris buffer 0,2M pH 7,5	1 ml
ATP 20 mM	0,1 ml
$MgCl_2 6H_2O$ 1M	0,1 ml
NADP 1% (TPN)	0,1 ml
Distilled Water	1,5 ml
	2,8 ml

200 µl of reagent mix was also added to 200 µl of 1 mM glucose standard and 200 µl of distilled water (used as the blank) and their absorptions at 340 nm recorded.

10µl of HK/G6PDH suspension (Boehringer Cat. No. 127825) was added to each cuvette and after standing for 30 minutes, the absorption at 340 nm was again read.

The glycogen content was calculated from the following formula:

$$\frac{\left(\frac{\text{Optical Density difference}}{0{,}414}\right) - (\text{baseline}) \times (\text{Vol in cuvette} = 3\text{ml})}{\text{wet wt of sample (mg)}}$$

This gives the glycogen content in mmole glucose equivalents kg^{-1} wet weight.

The recovery was calculated by $\frac{\text{Std reading}}{0{,}414} \times 100$

The recovery during the experiments was greater than 92%.

II Muscle Phosphofructokinase (PFK) Activity

The muscle sample was weighed and diluted 1 in 10 with a homogenating buffer consisting of

50 mM triethanolamine HCl

2 mM $MgCl_2$

1 mM EDTA

30 mM Mercaptoethanol

2 mM glycerol : for stabilising effect

1 mM 2-oxogluterate :

Keeping the tube surrounded by ice, the muscle was then homogenated for 10 seconds (Ultra TURRAX-TP18/10 Janke and Kunkel - Germany, setting 4). It was then centrifuged for 1 minute at 4°C (2000 r.p.m.) and the supernatant fluid decanted off for measuring.

Next, 10µl of the supernatant fluid was added to a cuvette with the reagent mixture which consisted of:

1 ml Tris - HCl - KCl - $MgCl_2$ - BSA buffer pH 8.2

10µl ATP 100 mM

10µl AMP 200 mM

10µl NADH 100 mM

10µl F-6-P 100 mM

* 5µl adolase
* 5µl glycerol - 3 - phosphate dehydrogenase
* 5µl 1:10 Triosephosphate isomerase
* added just prior to the addition of the supernatant fluid

The mixture was agitated and read to extinction at 340 mm, (Beckman Spectrophotometer - Model 35). The milli absorbance units (m.A.U) per minute were calculated from the slope of the curve.

The PFK activity was calculated according to the equation

$$\frac{\text{m.A.U.}}{6{,}2} \times \frac{\text{total vol cuvette (ml)}}{1000} \times \frac{1000}{\text{Vol extract used (ml)}} \times \frac{1}{\text{tissue wt (mg)}} \times \text{Vol Homogenising medium (ml)}$$

m.A.U. = milli absorbance units in one minute at 340 n.m.
This gave the value of PFK activity in $mol^{-1}min^{-1}g$ wet wt.

III Muscle Malate Dehydrogenase (MDH) activity

The muscle sample was weighed and diluted 1 in 30 with a homogenating buffer consisting of:

0.1 M KPO_4 at PH7.4 containing 0,1% albumin.

The muscle in ice cold buffer was homogenated for 10 seconds. (Ultra TURRAX-TP 18/10 Janke and Knukel - Germany B-12, Branson Sonic Power Company) and sonicated in ice for 15 seconds (Sonifer Model B-12, Branson Sonic Power Company). It was then centrifuged for 1 minute at 4°C (2000 r.p.m.) and the supernatant fluid decanted off for measuring.

The supernatant was further diluted 1 in 10 with additional homogenizing buffer.

Next 0.1ml of the muscle homogenate was added to a curvette with the reagent mixture consisting of:

2,7ml 0.1M KPO_4 at PH 7.4

0.1ml 0.006 M NADH in the cold 5mM KPO_4 PH 7.4

0.1ml 0.00M cis-oxaloacetic acid in ice cold 5mM KPO_4 PH 7.4.

The mixture was agitated and read to extinction at 340 nm (Beckman Spectrophotometer - Model 35). The milli absorbance units per minute was calculated from the slope of the curve.

The MDH activity was calculated according to the equation:

$$\frac{\text{m.A.U.}}{6,2} \cdot \frac{Vt}{Vs} \cdot \text{dilution} \left(\frac{1}{\quad}\right) = \text{Umg}^{-1} \qquad (300)$$

Vt - total volume in curvette

Vs - sample volume in curvette

U - the amount of enzyme causing the oxidation of one micromole of NADH per minute at 25°C and PH 7.4.

APPENDIX II

STATISTICAL METHODS

II Statistical Methods

Paired data were analyzed by the one-tailed Mann-Whitney U test. This non-parametric test was used due to the small sample sizes and therefore avoids the parametric t tests assumption of a normal distribution.

The value of U (the statistic used in this test) is given by the number of times that a score in the group n_2 precedes a score in the group with n_2 cases in the rankings. In cases where n does not exceed 8 a p-value may be directly calculated from tables. A $p<0,05$ was accepted as statistically significant.

REFERENCES

Appel H. Late results after menisectomy in the knee joint. A clinical and roentgenologic follow-up investigation. Acta Orthop Scand 1970; Suppl 133.

Arvidsson I, Eriksson E, Haggmark KT, Johnson RJ. Isokinetic thigh muscle strength after ligament reconstruction in the knee joint. Results from a 5-10 year follow up after reconstructions of the anterior cruciate ligament in the knee joint. Int J Sports Med 1981; 2:7-11.

Barford B, Bierring F. Treatment of lesions of the semilunar cartilages. Acta Chir Scand 1956; 110:422-435.

Baugher HW, Warren RF, Marshall JL, Joseph A. Quadriceps atrophy in the anterior cruciate insufficient knee. Am J Sports Med 1984; 12:192-195.

Bender JA, Pierson JK, Kaplan HM. Factors affecting the occurrence of knee injuries. J Assoc Phys Ment Rehab 1964; 18:130-134.

Bergstrom J. Muscle electrolytes in man. Scand J Clin Inves 1962; 68:11-13.

Bonar AA. Injuries of the semilunar cartilages in miners. A review of 200 cases with special reference to post operative disability time. Glasg Med J 1950; 31:197-205.

Booth FW, Seider MJ. Recovery of skeletal mucsle after 3 months of hindlimb immobilization in rats. J Appl Physiol Respirat Environ 1979; 47:435-439.

Booth FW. Effect of limb immobilization on skeletal muscle. J Appl Physiol Respirat Environ 1982; 52:1113-1118.

Bruner JM. Time, pressure and temperature factors in the safe use of the tourniquet. The Hand 1970; 2:39-42.

Caizzo VJ, Perrine JJ, Edgerton VR. Training-induced alterations of the in vivo force-velocity relationships of human muscle. J Appl Physiol Respirat Environ 1981; 51:750-754.

Calderwood JW, Dickie WR. Tourniquet paresis complicating tendon grafting. The Hand 1972; 4:53-55.

Cambell DE, Glen W. Foot pounds of torque of the normal knee and the rehabilitated post-menisectomy knee. J Am Phys Ther Assoc 1979; 59:418-421.

Cambell WC. In Cambell's Operative Orthopaedics, London, Henry Kimpton 3rd Ed. 1956; 129-191.

Carlson BM. The regeneration of skeletal muscle fibers following injury: a review. Med Sci Sport Exerc 1983; 15:187-198.

Chiu D, Wang H, Blumenthal R. Creatine Phosphokinase release as a measure of tourniquet effect on skeletal muscle. Arch Surg 1976; 111:71-74.

Chu J, Fox I. Pneumatic ankle tourniquet: clinical and electrophysiologic study. Arch Phys Med Rehabil 1981; 62:570-575.

Costill DL, Fink WJ, Habansky AJ. Muscle rehabilitation after knee surgery. Physn Sports Med 1977; 5:71-74.

Coyle EF, Feiring DC, Rotkis TC, Cote RW, Roby FB, Lee W, Wilmore JH. Specificity of power improvements through slow and fast isokinetic training. J Appl Physiol Respirat Environ 1981; 51:1437-1442.

Cushing H. Pneumatic tourniquets : with special reference to their use in craniotomies. Medical News 1904; 84:577.

Dahlback LO. Effects of temporary tourniquet ischaemia on striated muscle fibers and motor end-plates. Scand J Plast Reconstr Surg 1970 Suppl. 7.

Dahlback LO, Rais O. Morphologic changes in striated muscle following ischaemia. Acta Chur Scand 1966; 131; 430-440.

Dandy DJ, Jackson RW. The diagnosis of problems after menisectomy. J Bone Jt Surg 1975; 57-B: 349-352.

De Andrande JR, Grant C, Dixon AS. Joint distension and reflex muscle inhibition in the knee. J Bone Jt Surg 1965; 47-A:313-322.

Dery R, Pellitier J, Jacques A, Clavet M, Houde JJ. Metabolic changes in the limb during tourniquet ischaemia. Can Anaes Soc J 1965; 12:367-378.

Distefano VJ. Function, post-traumatic sequelae and current concepts of management of knee meniscus injuries: a review article. Clin Orthop Rel Res 1980; 151:143-146.

Dobner JJ, Nitz AJ. Post menisectomy tourniquet palsy and functional sequelae. Am J Sports Med 1982; 10:211-214.

Dubowitz V, Brooke H (1973) Muscle biopsy: a modern approach. London. W B Saunders.

Duffin D. Knee strength and function following menisectomy. Physioth 1977; 63:362-363.

Duthie JJR, MacLeod JG. Rehabilitation after menisectomy. Lancet 1943; 244: 197-199.

Edfeldt H, Thomson D. Early haemodynamic and respiratory changes following tourniquet release: influence of large doses of methylprednisolone. Acta Chir Scand 1980; Suppl 499:45-55.

Edström L. Selective atrophy of red muscle fibres in the quadriceps in long-standing knee joint dysfunction. J Neurol Sci 1970; 11:551-559.

Enger EA, Jennische E, Medegard A, Haljamae H. Cellular restitution after three hours of complete tourniquet ischaemia. Eur J Surg Res 1978; 10:230-239.

Enslin J. A follow up study of menisectomy on lower limb muscle strength and on knee joint function. S Afr J Physioth 1983; 39:93-100.

Evans WJ, Phinney SD, Young VR. Suction applied to muscle biopsy maximizes sample size. Med Sci Sports Exerc 1982; 14:101-102.

Fahmy NRM, Williams EA, Noble J. Meniscal pathology and osteoarthritis of the knee. J Bone Joint Surg 1983; 65-B:24-28.

Fairbank TJ. Knee joint changes after menisectomy. J Bone Joint Surg 1948; 30-B: 664-670.

Ferguson LK, Thompson WD. Internal derangements of the knee joint. An analysis of one hundred cases with follow up study. Ann Surg 1940; 112:454-470.

Flatt A. Tourniquet time in hand surgery. Arch Surg 1972; 104:190-192.

Fowler TJ, Danta G, Gilliat RW. Recovery of nerve function after a pneumatic tourniquet: observations on the hindlimb of baboon. J Neurol Neurosurg Psych 1972; 35:638-647.

Fry D. Letter: Inaccurate tourniquet guages. Br Med J 1972; 1:511.

Gardner VO, Caizzo VJ, Long ST, Baird RA, Prietto CA. The effect of tourniquet ischemia on the contractile properties of slow and fast muscle. Med Sci Sport Ex. 1984; 16:105 (Abstract).

Gear MWL. The late results of menisectomy. Br J Surg 1967; 54:270-272.

Gettman LR, Cutler LA, Strathman TA. Physiologic changes after 20 weeks of isotonic vs. isokinetic circuit training. J Sports Med 1980; 20:265-274.

Goldfuss AJ, Morehouse CA, Le Veau BF. Effects of muscular tension on knee stability. Med Sci Sports 1973; 4:267-271.

Goldspink DF. The influences of immobilization and stretch on protein turnover of rat skeletal muscle. J Physiol 1977; 264:267-282.

Grimby G. Isokinetic training. Int J Sports Med 1982; 3:61-64.

Grimby G, Gustafsson E, Peterson L, Renström P. Quadriceps function and training after knee ligament injury. Med Sci Sport Ex 1980; 12:70-75.

Haggmark T, Jansson E, Eriksson E. Fiber type area and metabolic potential of the thigh muscle in man after knee surgery and immobilization. Int J Sports Med 1981; 2:12-17.

Haljamae H, Enger E. Human skeletal muscle energy metabolism during and after complete tourniquet ischaemia. Ann Surg 1975; 182:9-14.

Hamberg P, Gillquist J, Lysholm J. The effect of diagnostic and operative arthroscopy and open menisectomy on muscle strength in the thigh. Am J Sports Med 1983; 11:289-292.

Harman JW. A histological study of skeletal muscle in acute ischaemia. Am J Path 1947; 23:551-565.

Harman JW, Gwinn RP. The recovery of skeletal muscle fibres from acute ischaemia as determined by histologic and chemical methods. Am J Path 1949; 25:741-756.

Helfet AJ. The management of derangements of the knee. Philadelphia. JB Lippincott 1963.

Heppenstall RB, Balderston R, Goodwin C. Pathophysiologic effects distal to a tourniquet in the dog. J Trauma 1979; 19:234-238.

Hislop HJ, Perrine JJ. The isokinetic concept of exercise. Phys Ther 1967; 47:114-117.

Hoshikawa Y, Kurosawa H, Fukubayashi T, Nakajima H, Watarai K. The prognosis of menisectomy in athletes. The simple meniscus lesion without ligamentous instabilities. Am J Sports Med 1983; 11:8-13.

Huckell JR. Is meniscetomy a benign procedure? A long term follow up study. Cand J Surg 1965; 8:254-260.

Hughston JC. A simple menisectomy. J Sports Med 1975; 3: 179-187.

Hurst LM, Weiglein O, Brown W, Campbell GJ. The pneumatic tourniquet: A biomechanical and electrophysiological study. Plast Reconst Surg 1981; 67:648-652.

Irwing GA, Christopher K. Inaccurate tourniquet pressure gauge readings - a wide spread problem. S Afr Med J 1984; 66:265-266.

Jackson JP. Degenerative changes in the knee after menisectomy. Br Med J 1968; 2:523-527.

Jenkins DG, Imms FJ, Prestidge SP. Muscle strength before and after menisectomy. A comparison of methods of post-operative management. Rheumatol Rehabil 1976; 15:153-155.

Johnson RJ, Kettlekamp DB, Clark W, Leverton P. Factors affecting late results after menisectomy. J Bone Joint Surg 1974; 56-A:719-729.

Jozsa, Kenner A, S'antha E. Effect of tourniquet ischaemia on intact, tenotomized and motor nerve injured human hand muscles. The Hand 1980; 12:235-240.

Karumo I. Intensive physical therapy after menisectomy. Ann Chirug Gynaec 1977; 66:41-46.

Kennedy TJ, Miller SH, Nellis SH, Buck D, Flaim SF, Graham WP, Davis TS. Effects of transient ischaemia on nutrient flow and anteriovenous shunting in canine hindlimb. Ann Surg 1981; 193:225-263.

Klenerman L, Crawley J. Limb blood flow in the presence of a tourniquet. Acta Orthop Scand 1977; 48:291-295.

Klenerman L, Biswas M, Hulands G, Rhodes A. Systemic and local effects of the application of a tourniquet. J Bone Jt Surg 1980; 62-B:385-388.

Krause WR, Pope MH, Johnson RJ, Wilder DG. Mechanical changes in the knee after menisectomy. J Bone Jt Surg 1976; 58-A:599-604.

Kurosawa H, Fukubayashi T, Nakajima H. Load-bearing mode of the knee joint. Physical behaviour of the knee joint with or without menisci. Clin Orthop Rel Res 1980; 149:283-290.

Lantzounis LA. Derangement of the menisci of the knee joint. Surg Gynae Obstet 1931; 53:182-188.

Larsson J, Hultman E. The effect of long term arterial occlusion on energy metabolism of the human quadriceps muscle. Scand J Clin Lab Invest 1979; 39:257-264.

Love RJM. Prognosis after removal of semi lunar cartilages. Br Med J 1923; 2:324-326.

Lundborg G. Ischaemic nerve injury. Scand J Plast Reconstr Surg 1970; Suppl 6.

Lysholm J, Gilquist J. Endoscopic menisectomy. A follow up study. Int Orthop 1981; 5:265-270.

MacAusland WR. Derangements of the semi-lunar cartilages: based on a study of 388 operative cases. Ann Surg 1931; 93:649-682.

McEwan JA. Complications of and improvements in pneumatic tourniquets used in surgery. Med Instrum 1981; 15:253-257.

MacDougall JD, Ward GR, Sale DG, Sutton JR. Biochemical adaptations of human skeletal muscle to heavy resistance training and immobilization. J Appl Physiol Respirat Environ 1977; 43:700-703.

Mander J. Early activity after menisectomy. J Bone Jt Surg 1964; 46-B:165.

Meekison DM. The operative treatment of injuries to the semi-lunar cartilages in personnel of the British Air Force. Can Med Assoc J 1944; 51:517-520.

Middleton RWD, Varian JP. Tourniquet paralysis. Aust NZ J Surg 1974; 44:148-188.

Miller SH, Price G, Buck D, Neeley J, Kennedy TJ, Graham WP, Davis TS. Effects of tourniquet ischemia and post ischemic oedema on muscle metabolism. J Hand Surg 1979; 4:547-555.

Miller SH, Lung RJ, Graham WP, Davis TS, Rusenas I. Acute effects of tourniquet ischemia on tissue and blood gas tensions in the primate limb. J Hand Surg 1978; 3:11-20.

Modig J, Kolstad K, Wigrin A. Systemic reactions to tourniquet ischemia. Acta Anaesthesia Scand 1978; 22:609-614.

Moore DH, Ruska H, Copenharver WM. Electronmicroscopic and histochemical observations of muscle degeneration after tourniquet. J Biophys Biochem Cytol 1956; 2:755-763.

Nicholas JA, Strizak AM, Veras G. A study of thigh muscle weakness in different pathological states of the lower limb. Am J Sports Med 1976; 4:241-248.

Ochoa J, Fowler T, Gilliat W. Anatomical changes in peripheral nerves compressed by a pneumatic tourniquet. J Anat 1972; 113:433-455.

O'Donoghue DH. Menisectomy. Phys Ther 1980; 60:1617-1623.

Oretorp N, Alm A, Ekstrom H, Gilquist J. Immediate effects of menisectomy on the knee joint. Acta Orthop Scand 1978; 49:407-414.

Paakkönen M, Alhava EM, Hanninen O. Effect of tourniquet ischaemia on muscle energy metabolism in menisectomy patients. Brit J Sports Med 1981; 15:167-171.

Patel D, Fahmy N, Sakayan A. Isokinetic and functional evaluation of the knee following arthroscopic surgery. Clin Orthop Rel Res 1982; 167:84-91.

Patterson S, Klenerman L, Biswas M, Rhodes A. The effect of pneumatic tourniquets on skeletal muscle physiology. Act Orthop Scand 1981; 52:171-175.

Patterson S, Klenerman L. The effect of pneumatic tourniquets on the ultrastructure of skeletal muscle. J Bone Jt Surg 1979; 613:178-183.

Peltier LF. Discussion: In Heppenstall BR, Balderston R, Goodwin C. Pathophysiologic effects distal to a tourniquet in the dog. J Trauma 1979; 19:239.

Perey O. Follow up results of menisectomy with regard to working capacity. Acta Orthop Scand 1962; 32:457-460.

Pipes TV, Wilmore JH. Isokinetic vs. isotonic strength training in adult man. Med Sci Sport Ex 1975; 7:262-274.

Prevoznik SJ. Injury from use of Pneumatic Tourniquets. Anaesthesiology 1970; 32:170.

Prietto CA, Caiozzo VJ, Prietto PP, McMaster WC. Closed versus open partial menisectomy. Post operative changes in the force-velocity relationship of muscle. Am J Sports Med 1983; 11:189-194.

Rorabeck CH. Tourniquet induced nerve ischaemia: an experimental investigation. J Trauma 1980; 20:280-286.

Rorabeck C, Kennedy J. Tourniquet induced nerve ischaemia complicating knee ligament surgery. Am J Sports Med 1980; 8:98-102.

Rudge P. Tourniquet paralysis with prolonged nerve block: an electrophysiological study. J Bone Jt Surg 1974; 56-B:716-720.

Sanders R. The tourniquet: Instrument or weapon? Hand 1973; 5:119-123.

Santavirta S, Kause A, Rindall K. Tourniquet ischemia clinical and biochemical observations. Ann Chir et Gynecol 1978; 67:210-213.

Santavirta S, Hökcrstedt K, Niinikoski J. Effect of pneumatic tourniquet on muscle oxygen tension. Acta Orthop Scand 1979; 49: 415-419.

Santavirta S, Höckerstedt K, Linden H. Pneumatic tourniquet and limb blood flow. Acta Orthop Scand 1978; 49:565-570.

Saunders KC, Louis DL, Weingarden SI, Waylonis GW. Effect of tourniquet time on post operative quadriceps function. Clin Orthop Rel Res 1979; 143:194-199.

Scully KE, Shannon JM, Dickersin RG. Factors involved in recovery from experimental skeletal muscle ischemia produced in dogs. I. Histologic and histochemical patterns of ischemic muscle. Am J Path 1961; 39:721-738.

Seymour N. The effectiveness of physiotherapy after medial menisectomy. Br J Surg 1969; 56:518-520.

Shakespeare DT, Rigby HS. The bucket-handle tear of the meniscus. A clinical and orthographic study. J Bone Jt Surg 1983; 65-B:383-387.

Shaw-Wilgis EF. Observations on the effects of tourniquet ischaemia. J Bone Jt Surg 1971; 53-A:1343-1346.

Sherman WM, Plyley MJ, Pearson DR, Habansky AJ, Vogelgesang DA, Costill DL. Isokinetic rehabilitation after menisectomy: A comparison of two methods of training. Physcn Sports Med 1983; 11:121-133.

Sherman WM, Pearson DR, Plyley MMJ, Costill DL, Habansky AJ, Vogelgesang DA. Isokinetic rehabilitation following surgery, a review of factors which are important to developing physiotherapeutic techniques following knee surgery. Am J Sports Med 1982; 10:155-161.

Sjostrom M, Neglin P, Friden J, Eklöf B. Human skeletal muscle metabolism and morphology after temporary incomplete ischaemia. Eur J Clin Invest 1982; 2:321-325.

Smillie IS. Injuries of the knee joint. 4th Edition. Baltimore Williams & Wilkins Co. 1971.

Smith B. Histochemical changes in muscle necrosis and regeneration. J Pathol Bacteriol 1965; 89:139-143.

Smith MJ, Melton P. Isokinetic versus isotonic variable resistance training. Am J Sports Med 1981; 9:275-279.

Snow MH. Metabolic activity during the degenerative and early regeneration stages of minced skeletal muscle. Anat Rec 1973; 176:185-204.

Sola OM, Christenson DL, Martin AW. Hypertrophy and hyperplasia in adult chicken anterior lattismus dorsi muscle following stretch with and without denervation. Exp Neurol 1973; 41:76-100.

Solonen KA, Hjelt L. Morphological changes in striated muscle during ischemia. A clinical and histological study in man. Acta Orthop Scand 1968; 39:13-19.

Sonne-Holm S, Fledelius I, Ahn NCN. Results after menisectomy in 147 athletes. Acta Orthop Scand 1980; 303-309.

Stalberg E, Segerström A, Johansson H, Olerud S. Emg-studier efter operation i blodtont falt. Nordmed 1970; 83:581.

Stock W, Bohn HJ, Isselhard W. Metabolic changes in rat skeletal muscle after acute arterial occlusion. Vasc Surg 1971; 5:249-255.

Strock PE, Majno G. Vascular responses to experimental tourniquet ischemia. Surg Gynae Obstets 1969; 129:309-318.

Strock PE, Majno G. Microvascular changes in acutely ischemic rat muscle. Surg Gynae Obstets 1969; 129:1213-1214.

Tapper EM, Hoover NW. Late results after menisectomy. J Bone Jt Surg 1969; 51-A:517-526.

Thorstensson A, Grimby G, Karlsson J. Force-velocity relations and fibre composition in human knee extensor muscles. J Appl Physiol 1976; 40:12-16.

Tountas CP, Bergman RA. Tourniquet ischemia: ultrastructural and histochemical observations of ischemic human muscle and of monkey muscle and nerve. J Hand Surg 1977; 2:31-37.

Urbanova D, Janda J, Mrhova R, Lindart J. Enzyme changes in the ischaemia of skeletal muscle and the effects of physical conditioning. A histochemistry study. Histochem J 1974; 6:147-155.

Van Handel PJ, Watson P, Troup J, Plyley M. Effects of treadmill running on oxidative capacity of regenerated skeletal muscle. Int J Sports Med 1981; 2:92-96.

Wagner KR, Carlson BM, Max SR. Developmental patterns of glycolytic enzymes in regenerating skeletal muscle after autogenous free grafting. J Neurol Sci 1977; 34:373-390.

Walker PS, Erkman MJ. The role of the menisci in force transmission across the knee. Clin Ortho Rel Res 1975; 109:184-192.

Wang CJ, Walker PS. Rotatory laxity of the human knee joint. J Bone Jt Surg 1974; 56-A:161-170.

Webb WR. Biologic foundations of surgery. Surg Clin North Am 1965; 45:267.

Weingarden SI, Louis DL, Waylonis W. Electromyographic changes in post menisectomy patients. JAMA 1979; 241:1248-1250.

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White TP, Villanacei JF, Morales PG. Influence of physical conditioning on autografted skeletal muscle. Med Sci Sports Ex 1981; 13:81 (Abstract).

Willien LJ. Bull U.S. Army Med Dept 1945; 4:452.

Wyn-Parry CB, Nicholas PJR, Lewis NR. Menisectomy: A review of 1723 cases. Ann Phys Med 1958; 4:201-215.

Yocum LA, Kerlan RK, Jobe FW, Carter VS, Shields CL, Lombardo SJ, Collins HR. Isolated lateral menisectomy. A study of 26 patients with isolated tears. J Bone Jt Surg 1979; 61-A:338-342.

Young A, Hughes I, Round JM, Edwards RHT. The effect of knee injury on the number of muscle fibres in the human quadriceps femoris. Clin Sci 1982; 62:227-234.

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