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Jarmo Kangas

OUTCOME OF TOTAL ACHILLES TENDON RUPTURE REPAIR, WITH SPECIAL REFERENCE TO SUTURE MATERIALS AND POSTOPERATIVE TREATMENT

FACULTY OF MEDICINE,
DEPARTMENT OF SURGERY,
DIVISION OF ORTHOPAEDIC AND TRAUMA SURGERY,
UNIVERSITY OF OULU

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Abstract

The purposes of the present research were to compare the outcome after Achilles tendon rupture repair in two postoperative regimens, to compare Achilles tendon elongation in two postoperative treatment methods, to compare the effects of two postoperative methods on motor performance aspects such as simple reaction time, choice reaction time, speed of movement, foot tapping speed and coordination, to test the mechanical properties of the recently developed poly-L/D-lactide (PLDLA) sutures and Maxon® sutures when implanted in the Achilles tendons of rabbits, and to study the histological tissue reactions and biodegradation of these sutures under the same conditions.

Isokinetic calf muscle strength scores at the last control check-up were excellent in 56% of the patients in the early motion group, good in 32%, fair in 8%, and poor in 4%, whereas the scores in the cast group were excellent in 29% of cases, good in 50% and fair in 21%. The ankle performance scores were excellent or good in 88% of the patients in the early motion group, fair in 4% and poor in 8%, whereas the scores in the cast group were excellent or good in 92% of cases and fair in 8%. No significant differences were seen between the two groups at 3 months and at the last control checkups with regard to pain, stiffness, subjective calf muscle weakness, footwear restrictions, range of ankle motion, isokinetic calf muscle strength or overall outcome. The complications included 1 re-rupture in the early motion group and 1 deep infection and 2 re-ruptures in the cast group.

AT elongation occurred in both groups, but was somewhat less marked in the early motion group. The AT elongation curves rose at first and then fell slowly in both groups. The patients who had less AT elongation achieved a better clinical outcome. AT elongation did not correlate significantly with age, body mass index or isokinetic peak torques.

The recovery of motor performance functions such as simple reaction time, choice reaction time, speed of movement, foot tapping speed and coordination did not depend on the two postoperative regimens. The motor functions of the operated leg had obviously recovered to the level of the non-operated leg 12 weeks after the operation.

Sutures made of PLDLA were used successfully for Achilles tendon repair in rabbits. There was no significant difference between the *in vitro* and *in vivo* tensile strength retention of the sutures. By comparison with Maxon®, PLDLA was found to have a lower initial tensile strength but more prolonged strength retention. The breaking strength values of the Achilles tendons repaired with sutures of these types were not significantly different at 6 weeks.

Intratendinous PLDLA sutures formed a thinner fibrous capsule during the 12-week follow-up period than did Maxon® sutures of the same diameter. The suture materials had not been totally absorbed by 12 weeks.

Keywords: achilles tendon rupture, biocompatibility, early motion, histomorphometry, immobilization in tension, Maxon®, motor performance, Polylactide suture, postoperative regimens, tendon elongation, tendon repair

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Jarmo Kangas

Abbreviations

AT	Achilles tendon
ATR	Achilles tendon rupture
DF	Dorsiflexion
HPM/BEP	Human Performance Measurement/Basic Elements of Performance
ICC	Intraclass correlation coefficient of reliability
MRI	Magnetic resonance imaging
PT	Peak torque
PTA	Peak torque angle
PW	Peak work
PL	Plantar flexion
SEM	Standard error of measurement
SD	Standard deviation
ROM	Range of motion
US	Ultrasonography
VAS	Visual analogical scale

List of original publications

This thesis is based on the following articles referred to the text by their Roman numerals:

I Kangas J, Pajala A, Siira P, Hämäläinen M & Leppilahti J (2003) Early immobilization in tension vs. early functional treatment of the musculotendinous unit after Achilles rupture repair. J Trauma 54:1171–1181.

II Kangas J, Pajala A, Ohtonen P & Leppilahti J (2007) Achilles tendon elongation after rupture repair. A randomized comparison of two postoperative regimens. Am J Sports Med 35:59–64.

III Kauranen K, Kangas J & Leppilahti J (2002) Recovering motor performance of the foot after Achilles rupture repair. A randomised clinical study about early functional treatment vs. early immobilisation of Achilles tendon in tension. Ankle Foot Int 23: 600–605.

IV Kangas J, Paasimaa S, Mäkelä P, Leppilahti J, Törmälä P, Waris T & Ashammakhi N (2001) Comparison of strength properties of poly-L/D-lactide (PLDLA) 96/4 and polyglyconate (Maxon®) sutures: In vitro, in the subcutis, and in the achilles tendon of rabbits. J Biomed Mater Res 58:121–126.

V Kangas J, Pajala A, Leppilahti J, Ashammakhi N, J, Törmälä P & Waris T (2006) Histomorphometric analysis of poly-L/D-lactide 96/4 sutures in the gastrocnemius tendon of rabbits. Int J Artif Organs 29:893–899.

Contents

1 Introduction

Until the twentieth century treatment of Achilles tendon rupture was preponderantly non-surgical; various means of immobilization were used, including strapping, wrapping and braces for varying periods (Wills *et al.* 1986). From the 1920's onwards, however, surgery has been proposed as the treatment of choice. Thus Quenu & Stojanovitch (1929) stated that "rupture of the Achilles tendon should be operated on without delay". Christensen (1953) and Arner *et al.* (1958/59) compared patients treated operatively and conservatively and found better results in the former group, and it was following their work that surgery became popular.

There is still a lack of consensus on the best management of acute Achilles tendon rupture. Treatment can be broadly classified into operative (open or percutaneous) and non-operative (cast immobilization or functional bracing). The optimal postoperative rehabilitation protocol after surgical repair of an Achilles tendon rupture is unknown. Six-week cast immobilization is most common, but many early functional rehabilitation protocols have been implemented. Experimental studies have shown that even one week of immobilization can be detrimental for muscle tissue (Hurme *et al.* 1990). Maxwell and Enwemeka (1992) showed that immobilization of rabbits' hind limb muscles in a shortened position resulted in serious atrophy within 4 weeks, which could not be reversed by subsequent immobilization at normal length. Rantanen *et al.* (1999) showed that postoperative immobilization of rats' hind limb muscles in tension led to significantly less extensive calf muscle atrophy than immobilization in a shortened position.

The suture materials used in Achilles tendon surgery have varied with time and surgical techniques. Only a few comprehensive studies on the tissue reactivity of suture materials can be found in the literature (Miller & Williams 1970, Pulvertaft 1965, Srugi & Adamson 1972, Ulin 1971, Wada *et al.* 2001, Kujala *et al.* 2003), together with some studies of their biomechanical properties (Trail *et al.* 1989, Wada *et al.* 2001, Kujala *et al.* 2003).

The main action of this study was to pay attention to clinical comparison of two postoperative treatment methods after Achilles rupture repair early functional treatment and early immobilization of the musculotendinous unit in tension by cast. An assessment is also made of whether the treatment results correlate with the elongation of the tendon. The effects of two postoperative treatment methods on motor aspects are compared in the

early phase of recovery after Achilles tendon rupture repair. The motor performance aspects measured are simple reaction time, choice reaction time, speed of movement, foot tapping speed and coordination.

The mechanical properties of two suture materials poly-L/D-lactide (PLDLA) and Maxon® sutures implanted in the Achilles tendons of rabbits are also tested and the resulting histological tissue reactions and biodegradation of the materials are evaluated.

2 Review of the literature

2.1 Anatomy of the Achilles tendon (AT)

The Achilles tendon, the common tendon of the gastrocnemius and soleus muscles, is the largest tendon of the human body. The gastrocnemius muscle has its origin above the knee joint, on the dorsal aspect of the distal femur, while the soleus muscle originates below the knee joint, at the posterior aspect of the proximal tibia and fibula. The muscle fibres from the gastrocnemius extend 11–26 cm above the calcaneus and those of the soleus 3–11 cm above it (Cummins *et al*. 1946). An anomalous soleus muscle may occasionally extend more distally along the tendon or be inserted separatively into the upper surface of the calcaneal bone (Lorenzon & Wirell 1987, Nelimarkka *et al.* 1988, Leppilahti *et al*. 1990). The AT is formed by the three broad, flat aponeuroses from the gastrocnemius and the soleus. The tendon is rounded and narrow in shape at its midpoint and finally fans out at the insertion. As the AT descends, its fibres rotate by up to 90° so that the posterior gastrocnemius tendon fibres rotate anterolaterally and the anterior soleus fibres run posteromedially (Cummins *et al.* 1946, Stein *et al.* 2000) (Fig. 1). The AT profile and cross-sectional area vary from 0.8 to 1.4 cm^2 along the course of the tendon (O'Brien 1992).

The AT is covered by a thin, smooth epitenon. It does not have a true sheath, but the epitenon is surrounded by a paratenon, which on the dorsomediolateral side consists of several thin, gliding membranes which can move in relation to each other. The spaces between these are rich in mucopolysaccharides, which are necessary for the gliding function. On the ventral side the paratenon consists of fatty arolar tissue and contains blood vessels and connective tissue, which forms thin septal structures.

A B

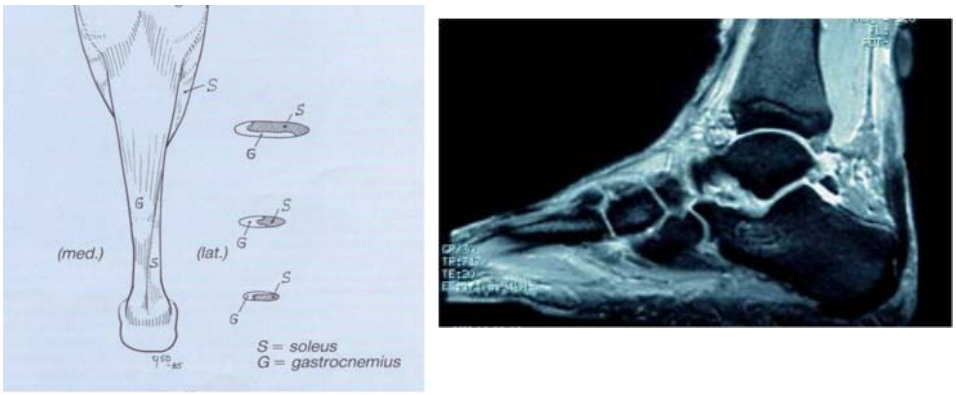


Fig. 1. A. The posterior aspect of the calf. B. Longitudinal MR image of ruptured Achilles tendon.

2.2 Biomechanics of the AT

The AT transmits the tension generated by the gastrocnemius and soleus muscles to the calcaneus. To do this effectively, the tendons must be capable of resisting high tensile forces with limited elongation (Best & Garrett, 1994). The biomechanical loading of the AT during normal locomotion varies from 600N in cycling and 4kN in sub-maximal hopping up to 9kN (11kN/cm2) in running at a speed of 6m/sec (Komi *et al.* 1992). The rate of collagen metabolism is relatively slow, the turnover time for tendon collagen being from 50 to 100 days (Curvin & Stanish 1984). There is normally a balance between synthesis and breakdown, but synthesis will exceed degradation during growth and following injury.

The tendon is not only able to transmit forces from the contracting muscle to the bone but also has the capability to deform and recover its original length. Its primary mechanical strength is dependent upon extracellular formation of triple-helical collagen fibrils with stabilizing molecular cross-links (Kadler *et al.* 1996). Parry *et al.* (1978) reported that the mechanical properties of tendons are related to the fibril diameter distribution, so that large fibrils can withstand higher tensile forces. Rotation plays an important role in tendon mechanics and function. The AT twists as it descends, with rotation beginning above the region where the soleus tends to join (Joza & Kannus 1997, O'Brien 1992).

The mechanical behaviour of the tendon depends on its cross-sectional area and length and on time. A larger tendon is stiffer and more force is needed to cause its failure, while elongation to failure does not change. With longer tendon fibres the stiffness decreases and the force to failure remains the same, but elongation to failure increases. Tendon collagen starts to fail at the elongation of 4% to 8%, whereas tendon elastin can elongate by up to 70% of its original length without rupture, and breaks at 150% (O'Brien 1992).

In the resting state, the collagen fibres and fibrils of the tendon are in a wavy configuration, but this disappears when the tendon is stretched by about 2%. As the collagen

fibres deform, they respond linearly to increasing tendon loads. If the strain placed on the tendon remains at less than 4% — that is, within the limits of most physiological loads, the fibres regain their original configuration on removal of the load, but at strain levels between 4 and 8% the collagen fibres start to slide past one another as the intermolecular cross-links fail, and at strain levels greater than 8% macroscopic ruptures occur because of tensile failure of the fibres and interfibrillar shear failure (O'Brien 1992). The tensile strength of tendons is high, being about 50 N/mm *in vitro* **(**Jozsa & Kannus 1997**).** A tendon with a cross-sectional area of 1 cm is capable of supporting a weight of 500 kg to 1000kg.

Morphological and biomechanical changes in the cells and extracellular matrix of the AT have been documented with ageing, and there is an increase in the cross-linking of the tropocollagen molecules which reduces the solubility of collagen. This means that the collagen becomes tougher, its tensile strength is reduced, the fibres shrink, the tendon stiffens and it is more likely to tear (Ippolito *et al.* 1980). The tensile strength of the human AT increases from the age of 10 to 30 years (3.5 to 7.8 kp/mm^2 and falls gradually thereafter to 4.8 kp/mm^2 at the age of 70 years (Barfred 1973). The maximal voluntary force of the male triceps surae drops from 1895 N at an age of 26 years to 1141 N at 71 years, a decrease of 40% (Mc Donagh *et al.* 1984).

The age of the individual and the size of the AT are important factors for its biomechanical properties and its capability to cope with high stress levels. Younger individuals have significantly higher tensile rupture stress and lower stiffness (Therman *et al.* 1995), while increased age, body height and cross-sectional calf muscle size correlate significantly with thicker Achilles tendons (Koivunen-Niemelä & Parkkola 1995). The crosssectional area of the AT is larger in runners than in non-runners (Rosager *et al.* 2002), and larger in elderly athletes than in sedentary men (Kallinen & Suominen 1994). This suggests that chronic exposure of the AT to loading results in tendon adaptation in man which is on a par with exercise-induced tendon hypertrophy in animal models (Woo *et al.* 1980, Birch *et al.* 1999).

Immobilization decreases collagen synthesis and increases its degradation. The number and size of the collagen fibre bundles, the water content and the total glycosaminoglycan content will all diminish (Tipton *et al.* 1986, Karpakka 1991). The tensile strength of the tendon is markedly reduced. The low metabolic rate of the tendon nevertheless means that the atrophy effects are slow and not as dramatic as in muscle. Immobilization causes muscle atrophy, which is slower and less severe with the ankle in a neutral position than with immobilization in the shortened position (Baker & Matsumoto 1988). The histochemical changes leading to the atrophy of tendon begin a few hours after cast immobilization (Booth 1982, 1987).

2.3 Achilles tendon rupture (ATR)

2.3.1 Nomenclature of ATR

ATR may be total or partial, closed or open and acute or late. The object of this thesis is an acute, closed, total rupture of AT. An acute or early rupture is one with a delay in treatment of one week at the most, while the terms late, neglected, or chronic rupture have been used to describe a rupture with a delay in treatment of 4 weeks or more. Re-rupture means a repeated rupture, often occurring soon after treatment of the previous ATR.

2.3.2 Epidemiology of ATR

ATRs were not common up to the 1950s (Barfred *et al.* 1970), since when the incidence is increasing (Nillius *et al.* 1976, Leppilahti *et al.* 1996, Rantanen *et al.* 1993, Nyyssönen & Lüthje 2000). Nillius *et al.* (1976) reported an increased incidence in Malmö, Sweden, during the period 1950–1973, with a peak age-specific incidence of $8.5/10^5$ per year at ages of 40 to 50 years. Rantanen *et al.* (1993) reported the incidence in the area served by Salo District Hospital in Finland during the years 1980 to 1991 to be $2/10^5$ inhabitants, while according to Leppilahti *et al.* (1996) the average incidence of ATR in the city of Oulu, Finland, increased from 2 $/10^5$ inhabitants in 1979 to 1986 to 12 in 1987 to 1994, with a peak incidence of 18 in 1994. The main reason for the rapid increase in ATRs in the late 1980s was probably an increase in the popularity of recreational sports.

The majority of patients with ATR are men, the ratio varying from 2:1 (Carden *et al.* 1987) to 19:1 (Zollinger *et al.* 1983). The peak incidence of ATR is between 30 and 40 years of age, which is lower than for other spontaneous tendon ruptures (Jozsa *et al.* 1989). Patients are often engaged in sedentary work and professional occupations (Arner & Lindholm 1959, Jozsa *et al*. 1989, Hooker 1963, Inglis & Sculco 1981). ATRs are most frequently unilateral and slight left leg predominance has been reported by some authors (Jozsa *et al*. 1989, Hooker 1963, Hattrup & Johnson 1985). Bilateral total ATRs are infrequent, and only case reports have been published on simultaneous bilateral ATRs. This usually occurs in older patients with systemic disease or a history of long-term corticosteroid medication (Cowan & Alexander 1961, Smaill 1961, Lee 1961, Melmed 1965, Haines 1983, Price *et al*. 1986, Weinstabl & Herz 1990, Orava *et al*. 1996).

About 75% of all ATRs are related to sports, recreational sports demanding sudden acceleration and jumping (Jozsa *et al.* 1989, Leitner *et al*. 1991). Ball games provide more than 60% of cases in many series (Nillius *et al.* 1976, Cetti *et al*. 1993, Jozsa *et al.* 1989, Möller *et al.* 2001), but there are considerable national differences in the frequencies of particular sports (Järvinen1992). Only 8 to 20% of ATR patients are competitive athletes, while 75% are recreational athletes and 10 to 12% do not take part in any sports (Nistor 1981, Leppilahti 1998, Möller *et al.* 2001).

Only a very few patients have symptoms in their AT before rupture. Maffulli (1999) reported that 5% of 176 ATR patients had previous AT symptoms. Nestorson *et al*. (2000)

reported that out of 25 AT rupture patients who were older than 65 years, 11 (44%) had had AT symptoms before rupture. In the series of Leppilahti *et al.* (1998) such individuals differed significantly with respect to age, sports activity and injury mechanism from those without previous AT symptoms.

2.3.3 Etiology of ATR

The rupture mechanism can be either indirect or direct trauma to the tendon. Arner and Lindholm (1959) described 3 main types of indirect trauma capable of causing rupture: pushing off with the weight-bearing forefoot while extending the knee joint, as occurs at the start of a sprint, running, and certain types of jump, sudden unexpected dorsiflexion of the ankle, such as occurs when slipping on a stair or ladder or stumbling into a hole or in a sudden forward fall, and violent dorsiflexion of a plantar-flexed foot, as can occur on landing when jumping or falling from a height.

The exact pathogenesis of ATR is not known. The two most frequently discussed theories involve the degeneration theory and the mechanical theory. According to the degeneration theory repetitive microtrauma and hypovascularity in the tendon are predisposing factors to the chronic degeneration, which leads to a rupture without excessive loads being applied. This theory has been supported by angiographic (Carr & Norris 1989) and histological (Kannus & Jozsa 1991) findings.

ATR may be associated with the use of anabolic hormones (Michna & Hartmann 1989, Laseter & Russell 1991) or fluoroquinolone antibiotics (Jagose *et al.* 1996, McGarvey *et al.* 1996). There are clinical case reports of ATRs related to the use of corticosteroids either systemically (Smaill 1961, Melmed 1965, Baruah 1984) or locally (Kleinman & Gross 1983), but there are no rigorous published studies that evaluate the risk of rupture associated with local corticosteroid injections. ATR can also be associated with systemic diseases such as rheumatoid arthritis, SLE and gout.

2.3.4 Diagnosis of ATR

In most cases the history of ATR is typical (Maffulli 1998) and the diagnosis is easily made clinically. The patients usually report a sudden pain in the calcaneal area, and have often heard a "pop" or snap in the AT region. Occasionally the pain may be slight or even absent. Christensen (1953/4) reported painless ruptures in 19 out of 57 cases. There are often no symptoms prior to the rupture. Lea and Smith (1972) reported 4% of patients to be symptomatic (manifested by pain, tenderness or stiffness in the Achilles tendon region) prior to rupture, while the figure was 18% for Bradley and Tibone (1990) and 32% for Böhm *et al.* (1990). A direct injury mechanism is rare.

ATRs typically occur 2 to 6 cm proximal to the tendon insertion on the calcaneus, and with decreasing frequency proximally and distally (Schönbauer 1964, Fox 1975). Almost always there is a palpable gap in the tendon. The longer the time elapsing between rupture

and examination, the more difficult it may be to palpate the gap at the rupture site on account of oedema, haematoma.

ATRs may also present as an active plantar flexion of the foot with the long toe flexor muscles. About 20% of ruptures (12 to 28%) are missed in this way, leading to treatment delay (Inglis 1976, Carden *et al.* 1987, Simmonds 1957). There are many diagnostic tests available. In Simmond's test (Simmonds 1957) there is absent or reduced plantar flexion, while Thompson's test involves squeezing the calf, with consequent failure to achieve plantar flexion (Thompson & Doherty 1962). In the sphygmomanometer cuff test described by Copeland (1990), the sphygmomanometer is applied around the bulk of the calf muscle with the knee flexed 90°. The cuff is inflated to approximately 100 mm Hg with the ankle plantar flexed. Passive dorsiflexion of the ankle is then performed by pressing on the sole of the foot. Only a flicker of movement is seen in the column of mercury if the AT is completely ruptured, while if the tendon is intact, the column will rise to approximately 140 mm Hg depending on the patient's normal value, as tested on the contralateral calf.

The diagnosis can be confirmed by ultrasonography or magnetic resonance imaging. US examination is highly investigator dependent, but it is cheap, rapid and well available. MRI has many advantages, including superior soft-tissue contrast, non-invasiveness, direct multiplanar imaging and lack of ionizing radiation (Panageas *et al.* 1990, Mink *et al.* 1991). It is quite expensive and timeconsuming, however, and limited in its availability.

The complaints and diseases which should be taken into account in the differential diagnosis of ATRs are partial ATR, acute AT peritendinitis, tennis leg (medial gastrocnemius tear), calf muscle strain and rupture, posterior tibial stress syndrome, ligament injuries in the ankle, fractures of the ankle and calcaneus, posterior tibial tendon injury and peroneal injuries.

In most cases the diagnosis can be made clinically and no specific imaging is required.

2.4 Treatment of ATR

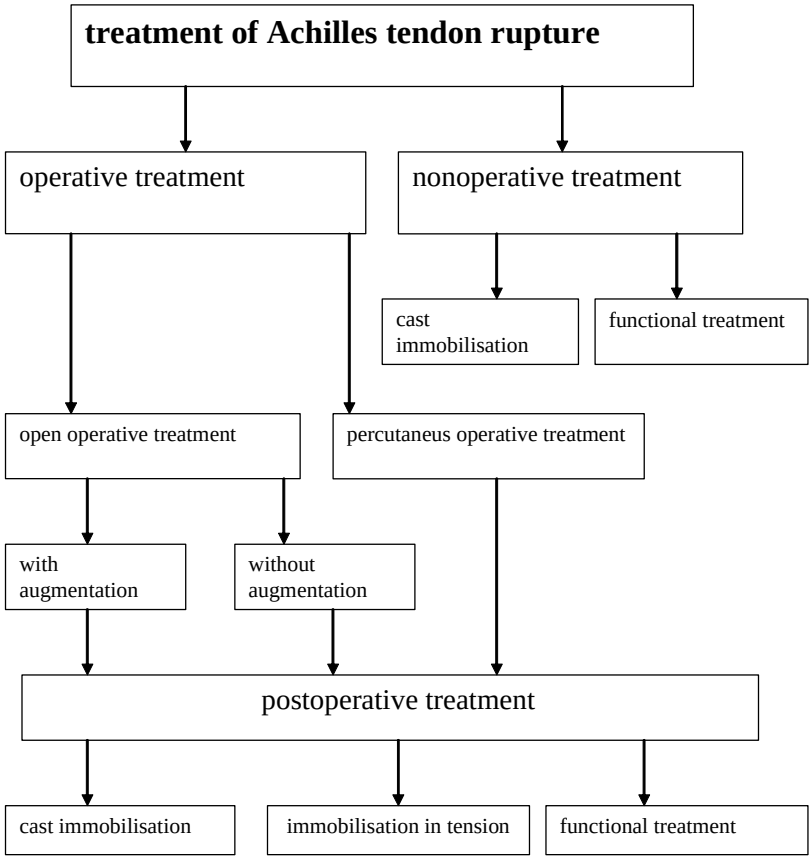


Fig. 2. Flowchart of treatment methods of ATR according to the literature and this study.

2.4.1 Surgical treatment

2.4.1.1 Surgical techniques

There is no single, uniformly accepted surgical technique for AT repair. Operative techniques can be classified into open and percutaneous ones, the former generally being used for athletes and young, fit patients and the latter for those who do not wish to have an open repair (e.g., for cosmetic reasons). Non-operative treatment has been preferred for the elderly patients (Maffulli 1999).

Open operative techniques can be divided into treatments with or without augmentation. In their quantitative analysis of operative treatments for AT, Wong *et al.* (2002)

recognised at least 41 different open techniques. There is only one randomised trial in which a weaker Mason suture technique is compared with a stronger, reinforced continuous six-strand suture technique for end-to-end repair (Mortensen *et al.* 1992), with no difference to be found between them. Although ATRs have also been successfully treated with simple end-to-end sutures under local anaesthesia (Cetti *et al.* 1981, Andersen & Hvass 1986, Keller & Bak 1989, Sejberg *et al.* 1990), many authors have combined simple tendon suture with plastic procedures of various types. Jessing and Hansen (1975) and Rantanen *et al.* (1993) compared the simple end-to-end suture technique with an augmentation technique in cases of early ATR and found no significant difference in the functional results. There are many other methods for augmentation of the suture. Quickley and Scheller (1980) used the plantaris tendon, White and Kraynick (1957) used the peroneus tedon for augmentation, Mann *et al.* (1991) used the digitorum longus tendon and Wapner *et al.* (1993) used the flexor hallucis longus tendon.

Ma and Griffith (1977) reported a new percutaneous technique using six small incisions for repairing ATRs, and many other authors have developed percutaneous techniques since then (Rowley & Scotland 1982, Klein *et al.* 1991, Webb & Bannister 1999). Lim J *et al.* (2001) reported good clinical results achieved by percutaneous tenorrhaphy.

2.4.1.2 Suture materials

The suture materials used in Achilles tendon surgery have varied with time and surgical techniques. Only a few comprehensive studies on the tissue reactivity of suture materials can be found in the literature (Miller & Williams 1984, Pulvertaft 1965, Srugi & Adamson 1972, Wada *et al.* 2001, Kujala *et al.* 2003), together with some studies of their biomechanical properties (Trail *et al.* 1989, Wada *et al.* 2001, Kujala *et al.* 2003).

The ideal suture material should have the following properties: high tensile strength, easily knotted with minimal loss of strength, inextensible, minimal tissue response, absorbable after tendon healing and easy to use (Trail *et al.* 1989).

Silk was used as a suture material in tendon repairs for many years. Its tensile strength at one month is only 60% of that at one week, and a continuing loss of tensile strength is noted thereafter, reaching zero within 24 months of surgery (Nathan 1972, Pulvertaft 1965). In addition silk, produces a marked tissue reaction.

Metallic suture materials are not widely used in tendon surgery, as they are difficult to use and they are weakened by kinking (Nyström & Holmlund 1983). Nitinol is a new candidate tendon suture material, with better manageability than stainless steel and good superelastic properties (Kujala *et al.* 2003). It has also been shown to have good biocompatibility with tendon tissue.

Synthetic non-absorbable suture materials are the most widely used, the most common being braided polyester (Ticron®, Ethibond®, Tevdek®), while others include monofilament polybutestor (Novafil®), polypropylene (Surgilene®) and monofilament nylon (Dermalon®). These materials entail some tissue reactions (Postlewait 1970, Wada *et al.* 2001), and their strength properties have been shown to decrease after implantation (Greenwald *et al.* 1994, Outlaw *et al.* 1998). Braided polyester seems to retain its strength exceptionally well after implantation (Greenwald *et al.* 1994).

Absorbable suture materials, of which there is a wide variety with differing inflammatory reaction, knot security and tensile strength properties, are more commonly used. The most popular materials have proved to be polyglactin (Vicryl), monofilament polydioxanone (PDS) and monofilament polyglyconate (Maxon). There are many reports on the breaking loads of suture materials before and after implantation in subcutaneous tissue and in implantation *in vivo* (Zislis *et al*. 1989, Herrman *et al*. 1970, Katz & Turner 1970, Herrman 1973, Frazza & Schmit 1971, Ruderman *et al.* 1973, Bourne *et al.* 1988, Trail *et al.* 1989, Wada *et al.* 2001). Mashadi and Amis 1992 evaluated tissue reactions brought about by polytrimethylene carbonate (Maxon) sutures in the flexor tendon of the third toe in a series of 48 chickens, evaluated the outcome both mechanically and histologically at 0, 5, 15 and 45 days after operation. Mechanical testing showed that the sutures kept their strength long enough to unite the tendon ends, but the high tissue reactivity of polytrimethylene carbonate during its absorption caused adhesions.

The synthesis of polylactide (PLA) was explored in the 1930s, but high molecular weight PLA was not introduced until 1955 (Schneider 1955). Developments in techniques for manufacturing absorbable biomaterials have made it possible to produce strong bioabsorbable sutures made of PLA with prolonged strength retention properties (Kulkarni 1966).

Polylactic acid (PLA) is one of the poly--hydroxy acids and belongs to the group of aliphatic polyesters that includes polyglycolic acid (PGA). Both are derivatives of cyclic diesters of glycolic and lactic acid, from which they were produced by ring opening polymerization, resulting in poly-alpha-hydroxy derivatives (Gilding & Reed 1979). The polymers are composed of repeating units of monomers, creating macromolecules with molecular weights typically from tens of thousands of daltons to more than 1 million daltons.

Polylactide is hydrolyzed in the body, metabolized into CO_2 and water, and eliminated through natural metabolic pathways (Hollinger 1983). The degradation process includes two phases. In the first, mainly physical phase, water molecules hydrolyse the chemical bonds of the polymer and cut the long polymer chains into short chains. The overall molecular weight and strength of the polymer are reduced during this depolymerization process, and the polymer fragments. The second phase involves phagocytosis of the fragments by macrophages, and the polymer mass rapidly disappears (Pietrzak *et al.* 1997). PLA is converted hydrolytically into lactic acid, which is further metabolized in the citric acid cycle to carbon dioxide and water, and the final products are excreted via the respiration or urine (Kulkarni *et al*. 1966, Brady *et al*. 1973, 1982, Hollinger & Battistone 1986).

P(L/DL)LA (also called PLDLA is more amorphous and less crystalline than pure PLLA and thus degrades faster (Kulkarni *et al.* 1971). Also, plates of this material have been shown to degrade more rapidly in subcutaneous tissue than on bone (Tschakaloff *et al.* 1994). SR-P(L/DL)LA plates and screws have been used clinically in orthognathic surgery with a skeletal stability pattern which is comparable to the ‘gold standard’ of titanium plates and screws (Haers & Sailer 1998). No clinical problems due to foreign-body reactions caused by P(L/DL)LA devices have been reported.

2.4.1.3 ***Postoperative treatment***

Up to the 1980s casting was the standard postoperative regimen after Achilles tendon rupture, regardless of the surgical technique used. The ankle was conventionally immobilized in an equinus position without weight bearing for four to nine weeks. Experimental studies have shown that immobilization of a muscle in a shortened position is deleterious, whereas immobilization in a stretched position markedly delays the development of atrophy. One week of immobilization was already found to be detrimental for muscle tissue (Hurme *et al.* 1990). Maxwell and Enwemeka (1992) showed that immobilization of rabbits' hindlimb muscles in a shortened position resulted in serious atrophy within 4 weeks, which was not reversed by subsequent immobilization at normal length. Rantanen *et al.* (1999) showed that postoperative immobilization of rats' hindlimb muscles in tension led to significantly less extensive calf muscle atrophy than immobilization in a shortened position. The latter is deleterious because myofibres very rapidly adjust to their new length by reducing the number of consecutive sarcomeres (Baker & Matsumoto 1988). This makes rehabilitation difficult, as the myofibres not only need to resume their original diameter but also to readjust to their normal length by neosynthesis of sarcomeres. The soleus muscle, which contains a high proportion of type I muscle fibres, is particularly susceptible to atrophy if immobilized in a shortened position (Häggmark & Eriksson 1979), whereas the gastrognemius is able to move when a below-knee cast is used, and is thus less affected.

Rantanen *et al.* (1993) reported good results obtained with Achilles rupture treatment using early postoperative immobilization of the ankle in a neutral position, but no controlled comparisons with other regimens have been reported. Since the late 1980s, there has been a trend towards functional postoperative treatment, which has been reported to be well tolerated, safe and effective in compliant, well motivated patients (Carter *et al.* 1992, Mandelbaum *et al*. 1995, Saw *et al*. 1993, Speck & Klaue 1998, Sölveborn & Moberg 1994, Troop *et al*. 1995). These studies did not include control groups, however, so that they fail to document the advantages and risks associated with early functional treatment in sufficient detail. Cetti *et al*. (1994) showed in a controlled study that patients treated for 6 weeks postoperatively with a mobile cast were able to resume sports activities sooner than those treated for 6 weeks with a below-knee cast with the ankle in a 20-degree equine position. Recently, Mortensen *et al.* (1999) have shown in a controlled study that early restricted motion shortens the time needed for rehabilitation.

2.4.2 Non-operative treatment methods

2.4.2.1 Cast immobilization

Lea and Smith (1972) treated tendon ruptures conservatively with casts and reported good results, which were subsedquently confirmed by other authors (Lillholdt & Munch-Jörgensen 1976, Stein & Lukens 1976, Termansen & Damholt 1979). Lea and Smith

(1972) recommended a regimen consisting of 8 weeks of immobilization in a walking plaster boot cast in the gravity equinus position. Gradual return to weight-bearing was encouraged. Use of a 2.5 cm heel lift for 4 weeks and active gastrognemius strengthening exercises were advocated after casting, This regimen is the most common management protocol for the conservative treatment of ATR according Movin *et al.* (2005). Blake *et al.* (1991) employed a below-knee cast for 12 weeks, initially in a maximally plantar-flexed position, with the angle gradually reduced until 0' of dorsiflexion was achieved. Electrical muscle stimulation and gradual weight bearing were begun at six weeks.

2.4.2.2 Functional treatment methods

Saleh *et al.* (1992) immobilized the ankle with a below-knee cast for three weeks (full equinus for 2 weeks) followed by weight bearing and controlled early mobilization with a splint. A Sheffield splint was fitted at the beginning of the fourth week and full weight bearing was allowed. As soon as active contraction of the triceps surae was achieved, normally after one week of use, the patient was allowed to discard the splint in bed at night. The splint was usually required for a total period of six to eight weeks, though in one case a period of three weeks was sufficient. The authors found this treatment superior to cast immobilization for eight weeks. McComis *et al.* (1997) treated 15 patients with two weeks of immobilization in an equinus cast followed 10 weeks of treatment with a custom-moulded polypropylene orthosis fixed at 45 degrees of plantar flexion. At eight weeks the patient was allowed to walk without crutches and to begin a stretching programme for plantar flexion, dorsiflexion, inversion and eversion. The orthosis was not worn during the stretching exercises. They reported good functional and subjective results. Petersen *et al.* (2002) randomised 50 patients with a first-time rupture of the Achilles tendon to either a traditional cast or a CAM walker and continued immobilization for eight weeks in both groups. They found less re-ruptures in the functional treatment group.

2.5 Outcome studies of ATR

2.5.1 Non-operative Treatment studies

2.5.1.1 Casting Immobilization Compared with Functional Bracing

There are only few studies comparing non-operative treatment in a cast with functional bracing (Saleh *et al.* 1992, Petersen *et al.* 2002), and in these cases the average time of immobilization in the functional bracing group were at least 8 weeks. A good functional outcome and low re-rupture rates were reported throughout, and the short-term results

were better in the splint group. Early functional bracing seems to advocate to rigid cast immobilization (Wong *et al.* 2002).

2.5.2 Open Operative Treatment Compared with Non-operative Treatment

Nistor (1981), who carried out the first randomized trial comparing surgical and non-surgical treatment, found the end results to be largely the same in both, but recommended non-surgical treatment because of the shorter morbidity and lack of hospitalization. In another randomized study surgical treatment using an end-to-end suture and 6 weeks of cast immobilization resulted in a higher resumption of sports activities, fewer patients with calf atrophy, better ankle movement and fewer complaints than non-operative treatment (Cetti *et al.* 1993). Möller *et al.* (2001) reported re-rupture rates of 20.8% after non-surgical treatment and 1.7% after surgical treatment ($p < 0.001$). Surgical and non-surgical treatment produced equally good functional results if complications could be avoided. The rate of re-rupture after non-surgical treatment was nevertheless unacceptably high.

Khan *et al.* (2005) find in their meta-analysis that the re-rupture rate is consistently higher among non-operatively treated patients than among operatively treated ones, although there was also a consistent finding of increased rates of complications (other than re-rupture) in the operatively treated group, with all studies demonstrating similar rates. In summary, non-operatively treated patients have a more than three times higher risk of re-rupture but have a minimal risk of other complications resulting from treatment.

2.5.3 Open Operative Repair Compared with Percutaneous Operative Repair

In a comparison of percutaneous and open surgical repairs (Bradley & Tibone 1990), the cosmetic results were better with percutaneous procedures and recovery of strength and motion was essentially the same as for both, but the rate of re-rupture was higher in percutaneous cases. Lim *et al.* (2001) performed a prospective randomized, multi-centre controlled trial in which they compared open and percutaneous repair of ATRs. They found a lower complication rate with the percutaneous method. Wong *et al.* (2002) reported a lower rate of wound complications in patients undergoing percutaneous repair, but they also noted that patients in this group had relatively high rates of other complications (most notably sural nerve injury), particularly when the procedure was combined with early active mobilization. Khan *et al.* (2005) noted a tendency for a lower overall rate of complications (particularly infections) in the percutaneously treated group, but this finding was based on pooled data on a small number of patients and there is some discrepancy between studies with regard to the rate of infection in cases of open treatment.

2.5.4 Postoperative Splinting: Cast Immobilization Compared with Cast Immobilization Followed by Functional Bracing

Early rehabilitation has been compared with immobilization after surgery for ATR in four randomized trials (Cetti *et al.* 1994, Mortensen *et al.* 1999, Maffulli *et al.* 2003, Costa *et al.* 2003). The results were good in both groups and the recovery was faster in the group which was treated with early rehabilitation using a brace. A variety of regimens were used for postoperative mobilization and rehabilitation, and the functional bracing group had a significantly lower rate of complications, particularly with regard to adhesion formation. The early mobilization group also tended to have a lower re-rupture rate (Khan *et al.* 2005).

Suchak *et al.* (2006) concluded that an early functional rehabilitation protocol for Achilles tendon ruptures improves patient satisfaction, reduces minor complications and entails no increase in the re-rupture rate. Larger-powered, prospective randomized studies are required to investigate the individual component of early weight bearing and early ROM in order to determine their effects on the outcome of Achilles tendon rupture repair and develop dynamic rehabilitation protocols to improve patient satisfaction and the clinical outcome.

2.5.5 Other trials

Several studies on the outcome of surgical treatment for ATR were published after 1930. According to Toygar (1947), reports on 86 patients with ATR became available between 1927 and 1947. The first fairly homogeneous assessments of the surgical treatment of ATR were published by Platt (1931), involving 11 patients, and Kager (1939), 38 patients. Silfverskiöld (1941) reported on a series of patients treated with a central rotation gastrocnemius flap, while Christensen (1954) reported on a series operated on with a gastrocnemius turn-down flap. Arner and Lindholm (1959) devised a method using two turn-down flaps and reported on 86 surgical repairs of the AT. They estimated the total number of cases of ATR described in 1954 to be 300–400.

Although non-surgical treatment became popular in the early 1970s, there have been a large number of non-randomized, non-comparative reports on surgical treatment (Inglis 1976, Shields *et al.* 1978, Kellam *et al.* 1985, Beskin *et al.* 1987, Soldatis *et al.* 1997, Leppilahti *et al.* 1998, Ingvar 2005).

Although only 47 cases of ATR treated non-surgically were reported during the period 1930–1971 (Möller 2001), Lea and Smith (1972) and Gillies and Chalmers (1970) both reported series of successful non-surgical treatments for ATR between 1968 and 1972. These patients were treated with at least eight weeks of plaster immobilization. Lo *et al.* (1997) found five series, including 106 patients, between 1953 and 1997 that met their criteria (Lillholdt & Munch-Jörgensen 1976, Nistor 1981, Persson & Wredmark 1979, Keller & Rasmussen 1984, Fruensgaard *et al.* 1992). All of these were of Scandinavian origin.

3 Purpose of the present research

The specific aims of the research were:

- To compare in a prospective, randomized clinical trial two postoperative regimens for Achilles tendon rupture (ATR) repair early functional treatment and early cast immobilization of the whole musculotendinous unit in tension.
- To compare Achilles tendon (AT) elongation after rupture repair in two postoperative regimens, early functional treatment on early cast immobilization of the whole musculotendinous unit in tension, and to test the null hypotheses that there is no difference in AT elongation between the two postoperative regimens and that AT elongation do not correlate with the clinical outcome.
- To examine the recovery of some motor performance aspects of the lower extremity and to compare the effects of two postoperative regimens of these motor aspects in the early phase of recovery after Achilles tendon rupture repair. The motor performance aspects measured were simple reaction time, choice reaction time, speed of movement, foot tapping speed and coordination.
- To compare the mechanical properties of the recently developed poly-L/D-lactide (PLDLA) sutures and Maxon® sutures when implanted in the Achilles tendons of rabbits.
- To compare the histological tissue reactions and biodegradation of the recently developed poly-L/D-lactide (PLDLA) sutures and Maxon® sutures when implanted in the Achilles tendons of rabbits.

4 Material and methods

4.1 Materials

4.1.1 Clinical studies (I, II, III)

In study I and II. One hundred and six patients were treated for an acute complete closed Achilles tendon rupture at Oulu University Hospital between July 1995 and July 1998, of whom 56 were excluded from the study on the grounds of age over 60 years (twelve patients), a delay of one week or more in treatment after the rupture (four patients), systemic corticosteroid treatment (two patients), local corticosteroid injection(s) around the Achilles tendon during the six months before the rupture (two patients), a previous Achilles tendon rupture on the opposite side (one patient), diabetes mellitus (one patient), living outside the county (twelve patients) and unwillingness to accept the protocol (23 patients). Thus the series consisted of 50 patients (47 men and 3 women, age range 21–55 years), 47 of whom had sustained the rupture during a sports-related activity, most frequently badminton (21 patients), volleyball (nine patients), soccer (five patients), tennis (four patients) and indoor hockey (three patients).

In study III. The population comprised 30 patients (3 competitive athletes, 20 recreational athletes, 7 non-athletes; 26 men and 4 women) operated on for an acute complete closed ATR at Oulu University Hospital between July 1995 and July 1996. The main criteria for inclusion were age <60 years, no previous ATRs, no neurological diseases nor diabetes mellitus, no systematic or local corticosteroid treatment, living inside the county and acceptance of the protocol.

4.1.2 Experimental studies (Papers IV, V)

In study IV. PLDLA monofilament sutures (Tampere University of Technology, Tampere, Finland) and polyglyconate (4.0) monofilament sutures (Maxon®, Cyanamid of

Great Britain Ltd., Gosport, UK), average diameter 0.228 mm, were used. The PLDLA monofilaments were melt-spun using an Axon BX-15 extruder (Axon, Sweden) having a die temperature of 256°C and oriented at an elevated temperature in a two-step process to a final draw ratio of 6.4. The final mean diameter of the filaments was 0.22 mm. The raw material used was a copolymer of L/D lactic acid (PLDLA) having an L/D monomer ratio of 96/4 and an intrinsic viscosity of 6.83 dL/g (PURAC Biochem B.V., Holland). The monofilaments were cut to a final length of 50 cm and a needle was attached to one end of each monofilament. The packed monofilaments were sterilized by g-irradiation with a minimum dose of 2.5 MRad. The sterile suture packages were opened just before the operations started.

Experimental animals: 32 New Zealand White rabbits, 12 weeks of age, weight range 2.6–3.3 kg.

In study V. Fifteen New Zealand White rabbits, 12 weeks of age, weight range 2.4–3.4 kg were operated on and sacrificed at 2, 6 and 12 weeks postoperatively, five rabbits in each group. The PLDLA monofilament sutures were implanted into the medial gastrocnemius tendon. Polyglyconate monofilament sutures of similar diameter (Maxon® 4-0, Cyanamid of Great Britain Ltd., Gosport, UK) were implanted in the contralateral gastrocnemius tendon. The histology was studied in hard-resin embedded samples. The thickness of the resulting fibrous tissue capsule was determined histomorphometrically.

4.2 Methods

4.2.1 Treatment methods of clinical studies (I, II, III)

4.2.1.1 Surgical treatment

All the patients were managed with the same operative technique as proposed by Silfverskiöld (1941). The operations were performed under spinal anaesthesia in a prone position using a tourniquet. A posteromedial skin incision was made, and the fascia and paratenon were divided along the same line. The tendon was repaired by the two modified Kessler (1973) suture technique with absorbable PDS® (polydioxanone) 2-0 gauge sutures (Ethicon, Somerville, New Jersey) and smaller apposition sutures with Vicryl® (polylactin, Ethicon). A central gastrocnemius aponeurosis flap was turned down over the suture line and stitched to the Achilles tendon with Vicryl®. After suturing, the titanium markers were placed on both sides of ruptured tendon ends. The ankle was then gently placed in a neutral position. The fascia was carefully resutured with Vicryl®, and the skin was closed with Ethilon® (nylon) sutures (Ethicon) (Fig. 3). At the end of the operation, a below-knee rigid plaster splint was applied with the ankle in a neutral position. The postoperative randomization group was not known at the time of the operation.

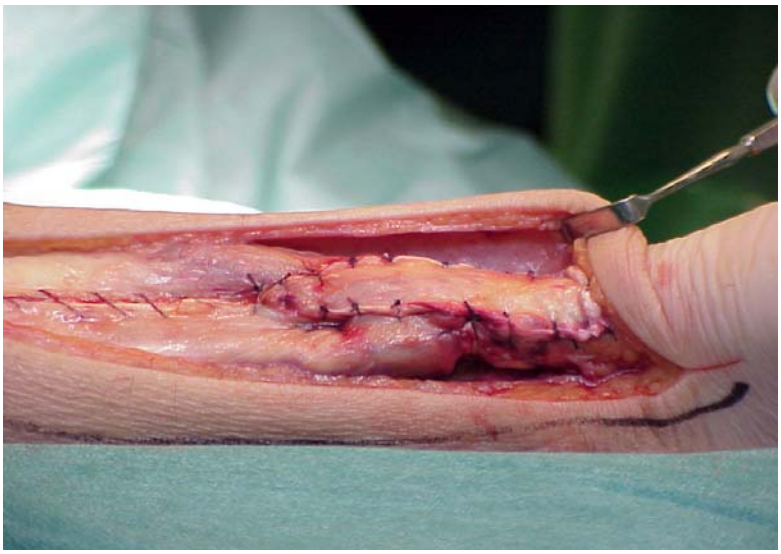


Fig. 3. A central aponeurosis flap was rotated down over the suture line as proposed by Silfverskiöld.

4.2.1.2 Postoperative regimens

The fifty patients were randomized postoperatively between regimens of either early mobilization (25 patients) or immobilization in tension (25 patients) group (group I), using randomly mixed sealed envelopes. The patients randomized into the early motion group had a below-knee dorsal cast (3M Soft cast) for six weeks, which allowed active free plantar flexion of the ankle whereas dorsiflexion was restricted to neutral (Fig. 4), while those randomized into the immobilization group were given a below-knee plaster cast (3M Scotchcast) with the ankle in a neutral position for six weeks (group II). Full weight bearing was allowed after three weeks in both groups.

The patients in both groups were instructed to do postoperative exercises according to a standard rehabilitation regimen. The regimen started with early ankle motion exercises in group II, concentric contractions of the ankle flexors and extensors in group I, and toe, knee and hip (group I) movement series in both groups. The number of series was increased at three weeks. Resisted ankle movements, ankle rotation exercises, standing on toes and heels, and movements with a rubber strip were added to the regimen at six weeks. Raising and lowering of the heels, ankle movements against a rubber strip and stretchings were included at 9 weeks. The programme included 10 to 25 repetitions of each exercise in three series three times daily at home. None of the patients received professional physiotherapy. Jogging was increased at 12 weeks, and all types of sports were permitted at 6 months.

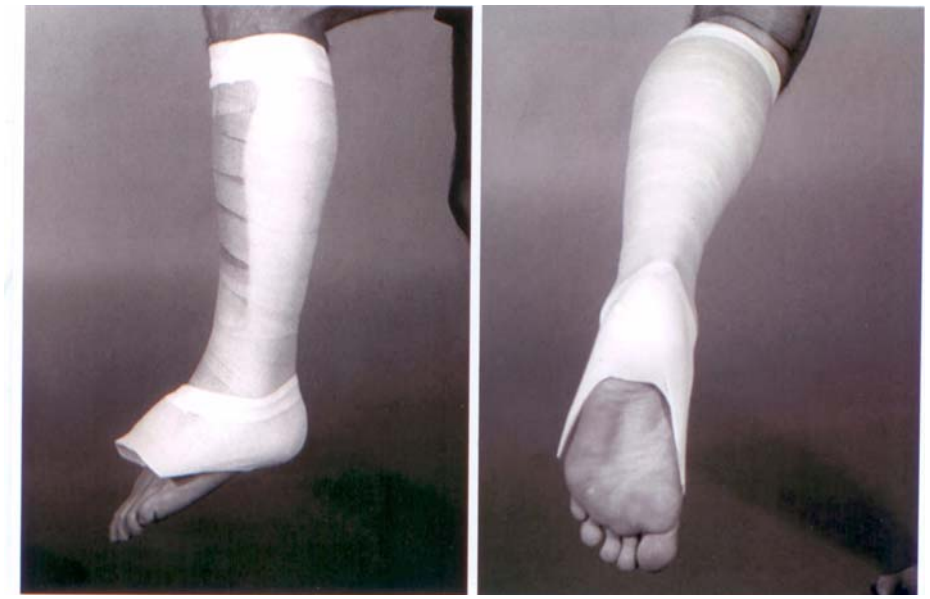


Fig. 4. A below-knee dorsal cast, which allows active free plantar flexion of the ankle whereas dorsiflexion is restricted to neutral.

4.2.2 Evaluation methods

4.2.2.1 Achilles tendon rupture score (I,II)

The patients were examined clinically at 1, 3, 6, 12 and 24 weeks postoperatively, and finally at a mean of 60 weeks. The outcome was assessed at the 3-month and final check-ups by the clinical scoring method described by Leppilahti *et al.* (1998). This included subjective factors such as pain, stiffness, muscle weakness, footwear restrictions and subjective outcome and objective factors such as the range of active ankle motion and isokinetic calf muscle strength. The patients were also asked to complete a written questionnaire independently. The clinical observers were not blinded to the treatment groups.

4.2.2.2 Strength measurement (I,II)

Isokinetic and isometric muscle function parameters were assessed for the two groups at the 3-month and final checkups using a computer-based Lido® Multi-Joint II isokinetic dynamometer (Loredan Biomedical, Inc., West Sacramento, CA). Isometric muscle function is muscle function without moving the joint and isokinetic muscle function is by use of machine the speed contraction is kept constant throughout the full range of motion. All

the isokinetic tests were performed by the same physiotherapist. All the patients were informed of the procedure, and a ten-minute warm-up period of ergometer cycling was included prior to the test. The testing position was supine, and the patient was fixed to the testing apparatus with straps round the foot and the pelvis, with the knee supported in extension (Fig. 5). The extent of ankle motion was from 40 degrees of plantar flexion to 20 degrees of dorsiflexion. Before testing, the patient performed some submaximal and maximal repetitions of the ankle flexion and extension movements at the isokinetic test velocity. The isokinetic dorsiflexion and plantar flexion strengths were measured, first at a speed of 60°/sec, then at 120°/sec and finally at 180°/sec after two minutes of rest. Five maximal voluntary muscular torque contractions were required. After the isokinetic tests, the maximal isometric plantar flexion strength was measured with the ankle in the neutral position. The isokinetic speed was used to analyse the strength results.

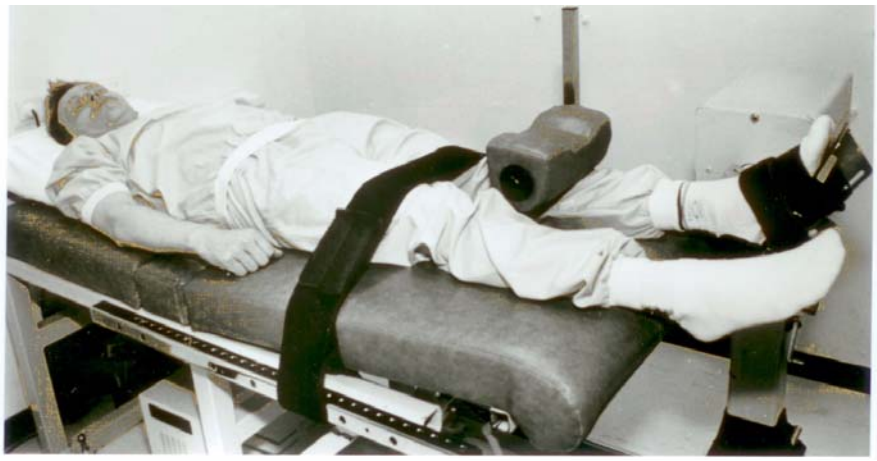


Fig. 5. Position of the patient in the Lido Multi-Joint II isokinetic dynamometer.

4.2.2.3 Radiographic measurements (II)

Standardized radiographs for measuring previously placed radiographic markers were taken on the first day postoperatively and at 1, 3, 6, 12 and 24 weeks, with a final radiograph a mean of 60 (SD 6.4) weeks postoperatively. The ankle was fixed in the brace in the plantigrade position and the distance between the x-ray source and the film plate was set at 100 centimetres, with the radiograph was focused on the midpoint of the Achilles tendon. The magnification of 1.1 was taken into account (Fig. 6).

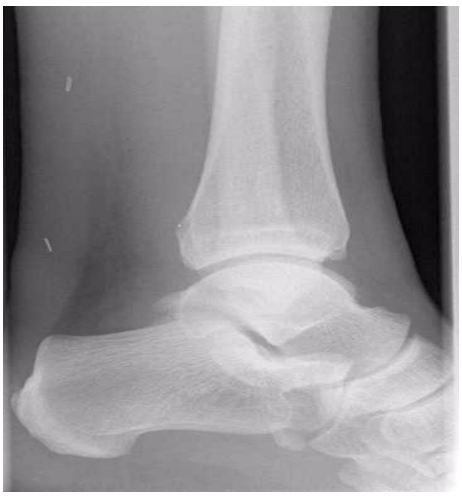


Fig. 6. The titanium markers applied on both sides of ruptured tendon ends.

4.2.2.4 The motor performance tests (III)

The patients were examined clinically 1, 3, 6, 12, 24 and 48 weeks after the operation, and motor performance functions were collected 12 and 24 weeks postoperatively. The results were compared between the operated and non-operated legs and between the immobilization and early motion groups.

Instrumentation. Motor control of the leg: The module for feet (BEP2) of the Human Performance Measurement/Basic Elements of Performance (=HPM/BEP) system (Human Performance Measurement, Inc. Arlington, TX 76004-1996) was used for the collection of motor performance data. This module is a multifunctional system designed to measure different motor aspects of the use of the feet, including reaction time, movement speed, tapping speed and coordination. It employs two red lights as visual stimuli and seven touch-sensitive plates divided into three regions. The foot tests are performed in the three regions of the module, all with the subject sitting (Fig. 7).

All the measurements on the subjects and controls were performed by the same person, and the subjects were given standardized instructions and explanations of the test procedure. All procedures were as described in the manual (Kondraske 1991). The tests were demonstrated, and each subject was allowed to perform three training trials before every measurement. Tests with anticipation errors or obvious delays (= reaction times >500 ms) were considered to have failed and were repeated. The number of tests and the measurement times were set by the Human Performance Measurement software (HPM/BEP, version 4.2).

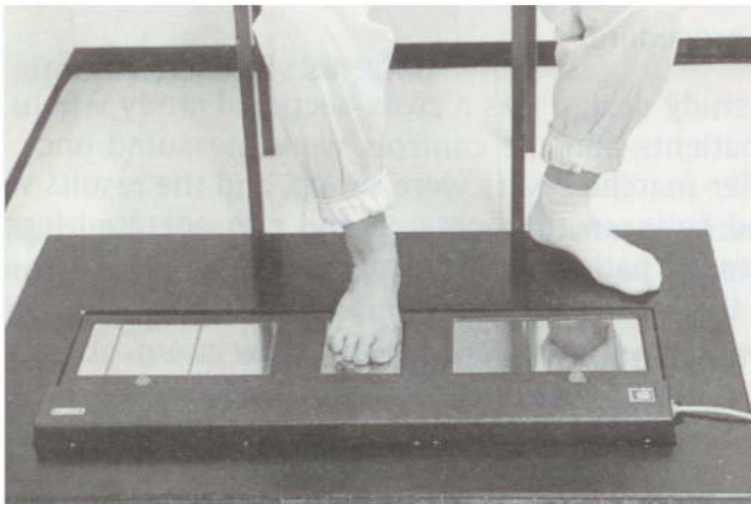


Fig. 7. The motor aspects of the feet were measured with the module for feet (BEP2) of the Human Performance Measurement/Basic Elements of Performance (HPM/BEP) system.

The test-retest reliabilities of the HPM/BEP2 tests have been assessed in detail by Kauranen & Vanharanta (1996), giving standard errors of measurement (SEM) and intraclass correlation coefficients of reliability (ICC) (Fleiss 1986) as follows: 2-choice reaction time: SEM 21.7, ICC 0.70, speed of movement: SEM 11.2, ICC 0.88, tapping speed: SEM 0.2, ICC 0.86, and lateral coordination: SEM 0.5, ICC 0.68.

The test subjects performed the following tests during each measurement session: 1. Simple reaction time (5 trials), 2. 2-choice reaction time + speed of movement (6 trials), 3. Foot tapping speed (2 repetitions) and 4. Coordination test (2 repetitions).

4.2.3 Experimental studies (Papers IV, V)

4.2.3.1 Comparison of strength properties of PLDLA 96/4 and polyglyconate (Maxon®) sutures (IV)

Operations. For the in vivo study, 32 New Zealand White rabbits aged 12–16 weeks were operated on. They were anaesthetized with pentobarbital (Mebunatt® 60 mg/mL, Orion, Finland), 1–2 mL/kg body weight diluted in 10 mL normal saline and administered by intravenous injection, and PLDLA and Maxon® monofilament sutures were implanted in the dorsal subcutaneous tissue of each of them. The Achilles tendon of the rabbit has three parts: the soleus tendon and the medial and lateral gastrocnemius tendons. In each of the 32 rabbits the soleus tendon of the right hind leg was cut at its distal part approximately 0.5 cm proximal to the calcaneal bone and the lateral gastrocnemius tendon was cut proximally at the musculotendinous junction. To gain extra tendon length, the proxi-

mal part of the soleus tendon and the distal part of the lateral gastrocnemius tendon were sutured together by the Kessler method using one suture. PLDLA sutures were used in 16 rabbits and Maxon® sutures in the other 16. The other cut tendon ends were left unsutured, because they were short. The left hind leg was not operated on and served as a control. The wounds were closed with 4.0 Ethilon® (Johnson & Johnson) sutures. No external splinting or support was applied.

The rabbits were returned to their cages to recover from the anaesthesia and were given a regular laboratory animal diet and normal care postoperatively. They were followed up for 1, 2, 4 and 6 weeks. After sacrifice (using an overdose of anaesthetic), the sutures were removed from the subcutaneous tissue and immersed in saline. The calcaneal tendons, calcaneal bone and calf fascia were also removed.

The strength measurements were performed immediately after removal from saline within 24 h of sacrifice.

Strength Measurements. The PLDLA and Maxon® sutures for the in vitro study were immersed in phosphate buffer saline solution, pH 7.4, at 37°C and specimens were retrieved at 1, 2, 4, 6, 8, 10, 13, 16, 19, 22 and 26 weeks. The buffer solution was changed every 2 weeks to keep the pH constant. The tensile strength tests were performed on wet microfilaments using a PC-controlled Instron 4411 materials testing instrument (Instron Ltd, High Wycombe, UK). The axial gauge length was 50 mm and the cross-head speed 30 mm/min. Five specimens were tested in each follow-up group in vitro, together with 5 specimens belonging to the in vivo study. Non-sterile 0-week PLDLA monofilaments were also tested to obtain reference values. When testing the tendon specimens the gauge length was 10–15 mm and the cross-head speed was 30 mm/min. Tensile strength was calculated by dividing the breaking strength (N) by the cross-sectional area (mm2).

In the case of repaired tendons the maximum force before breaking is presented, because of variation in the thickness of the repair tissue and the difficulty of obtaining accurate cross-sectional measurements (tensile strength was not calculated). The elongation of the repaired tendons was also calculated and expressed as the percentage increase in length before breaking.

Means, differences between means and 95% confidence intervals (CIs) for differences were then calculated. p values were calculated using a non-parametric (Mann–Whitney) test.

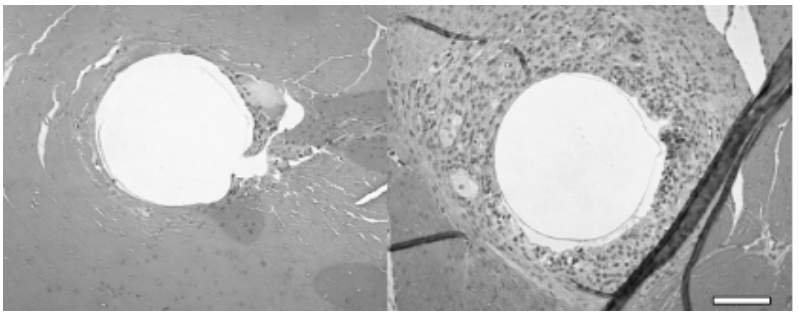
4.2.3.2 Histological characterization of PLDLA 96/4 sutures (V)

Operations. Fifteen New Zealand White rabbits, 12 weeks of age with a weight range of 2400–3400g were operated on. The rabbits were anaesthetized with an intramuscular injection of ketamine hydrochloride, 20mg/kg (Ketalar® 50mg/ml, Parke-Davis, Barcelona, Spain), and medetomidine hydrochloride, 0.3mg/kg (Domitor®, Orion-Pharma, Turku, Finland). Prophylactic cefuroxim (Lifurox®, Eli Lilly and Company, Indianapolis, Indiana, U.S.A), 20mg/kg, was given i.m. preoperatively. The rabbits were furred and cleaned with ethanol over the incision site, and a small incision was made over the medial side of the gastrocnemius tendon on both legs. A PLDLA monofilament was implanted deep inside the medial gastrocnemius tendon of the right leg with an already attached

needle and a polyglyconate (4.0) monofilament suture (Maxon®) was implanted deep inside the gastrocnemius tendon of the left leg. The material was placed parallel to the microfibrils of the tendon, leaving about 1.5–2 cm of material inside the tendon tissue. Both materials were left in place inside the tendon as such, without knotting or any mechanical attachment to surrounding tissues. The skin was closed with non-absorbable polyamide 4-0 sutures (Ethilon®, Johnson & Johnson, New Jersey, USA). The rabbits were allowed to move about freely in their cages postoperatively, and no external support was applied. They were housed in groups of three, in a room with temperature and humidity control and artificial illumination. Regular pelleted rabbit food and tap water were provided ad libitum

Specimen processing and evaluation methods. The rabbits were sacrificed using pentobarbital 180mg i.v. (Mebunat®, Orion-Pharma, Espoo, Finland), at two, six and twelve weeks postoperatively, five rabbits in each group. The gastrocnemius tendons were cut out in one piece and stored in 10% buffered formalin solution. After fixation, they were embedded in methylmethacrylate (Technovit®, Kulzer GmbH, Germany) by standard methods and specimens were cut transversely with a diamond saw in the area where the suture was located inside the tendon. Sections of thickness 30 µm were made using a Micro-Grinding system (EXAKT Appartebau, Germany). The sections were stained with haematoxylin and eosin for microscopic evaluation (Fig. 8). All microscopic samples were digitized using a Nikon Coolpix E950 digital camera (Nikon, Tokyo, Japan), a Nikon Eclipse E600 microscope (Nikon, Tokyo, Japan) and a 0.82–0.29x camera tube.

Data analysis. The thickness of the reactive fibrous tissue capsule that was around the sutures was measured by computer-assisted histomorphometry. A clock-like transparent template grid was centred over the displayed image of the sample and randomly rotated on the computer screen. Measurements were recorded as two-point distances at random intersections of the template and the features of the image were recorded with image analysis software UTHSCSA ImageTool (developed at the University of Texas Health Science Center at San Antonio, Texas and available on the Internet by anonymous FTP from maxrad6.uthscsa.edu). The spatial calibration was done by digitizing a 2000 µm object micrometer graticule (Ernst Leizt, Wezlar, Germany). The thickness of the fibrous tissue capsule was evaluated at 12 points around the implant. To avoid discrepancies, the measurements were made only on samples where the material was totally surrounded by tendon tissue. If the immediately surrounding tissue was of any other kind the sample was rejected, because we wished to study the reactions within the collagen matrix area of the tendon, which is a relatively avascular tissue (6) and any other surrounding tissue could be more vascularized, which might have affected the results. Samples where the material was located in endotenon or peritenon areas were rejected for the same reason. The digitally photographed samples were mounted in a random fashion.



A. PLDLA B. Maxon®

Fig. 8. Intratendineously implanted PLDLA suture in left and Intratendineously implanted Maxon® suture at six week.

4.2.4 Statistical methods

The statistical analysis was performed using the Statistical Package for Social Sciences (SPSS®, version 10.0 Inc. 44 N. Michigan Avenue, Chicago, Illinois 60611). Summary statistics for continuous variables are expressed as medianS with 25th and 75th percentiles. Spearman correlation coefficients were used to determine the correlations between AT elongation and clinical outcome and the T-test to calculate the differences in AT elongation. The results of the motor performance tests were analysed with Fisher's exact test. Two-tailed p-values are reported. Analysis with nonparametric statistics (Wilcoxon test for matched pairs and Mann-Whitney two-sample test) did not change the results, and parametric values were only reported.

The thickness of the fibrous tissue capsule is expressed as a median value together with the inter-quartile range (IQR, 25th–75th percentile). The values were compared by means of the Mann-Whitney test.

4.2.5 Ethics (I,II,III,IV,V)

All the studies were approved by the local Research Ethics Committee.

The guidelines of the Ethical Committee of the Oulu University Experimental Animal Centre for the care and use of experimental animals were observed throughout.

5 Results

5.1 Early postoperative AT immobilization in tension vs. early functional treatment (I)

Subjective result. Thirteen patients in group I (52%) were very satisfied at the last follow-up, eleven (44%) were satisfied with minor reservations and one (4%) was dissatisfied, whereas in group II nineteen patients (76%) were very satisfied, four (16%) were satisfied with minor reservations and two (8%) were satisfied with major reservations ($p = 0.06$, table 1).

Pain Relief. The mean VAS (visual analogical scale) was 2.17 (SD 2.7) in group I and 2.02 (SD 1.7) in group II one week postoperatively ($p = 0.08$), 0.83 (SD 1.2) in group I and 0.82 (SD 1.3) in group II at 3 weeks ($p= 0.797$) and 0.65 (SD 1.4) and 0.60 (SD 0.9) at 6 weeks ($p = 0.346$). Twenty-four Achilles tendons were painless at the 3-month check-up, while twelve were mildly painful, seven moderately so and six severely so ($p= 0.578$ between groups). One patient was excluded because of Achilles tendon re-rupture at 3 months. At the last check-up, twenty-one Achilles tendons (84%) were painless, three tendons (12%) were mildly painful and one (4%) was moderately painful in both groups (table 1).

Stiffness. Eleven patients in group I (44%) reported no Achilles stiffness at the last control visit and fourteen (56%) reported mild stiffness, whereas in group II seventeen patients (68%) reported no stiffness and eight (32%) reported mild stiffness ($p = 0.087$ between the groups, Table 1).

Subjective calf muscle weakness. Nineteen patients in group I (76%) had no subjective calf muscle weakness at the last check-up, four (16%) had mild weakness, one (4%) moderate weakness and one (4%) severe weakness, whereas in group II nineteen patients (76%) had no subjective calf muscle weakness, five (20%) had mild weakness and one (4%) moderate weakness ($p = 0.77$ between the groups, table 1).

Footwear restrictions. Seventeen patients in group I (68%) had no footwear restrictions at the last follow-up, seven (28%) had mild restrictions and one (4%) had moderate restrictions, whereas in group II twenty-three patients (92%) had no footwear restrictions and two (8%) had mild restrictions ($p = 0.096$ between the groups, table 1).

Range of motion. The range of motion was normal (5° active ROM difference between ankles) in eighteen patients in group I (72%) at the last control visit, mildly limited (6°-10° ROM difference between ankles) in five (20%), moderately limited (11°-15° active ROM difference between ankles) in one (4%) and severely limited (≥16° ROM difference between ankles) in one (4%), whereas in group II it was normal in nineteen patients (79%), mildly limited in four (17%) and moderately limited in 1 (4%) ($p = 0.77$, table 1).

Isokinetic and isometric calf muscle strength. Peak torque (PT). The mean relative peak torque (Nm) deficits for plantar flexion in the injured limb at 3 months were 20.8, 17.9 and 5.9% at 60, 120 and 180°/sec, respectively, for group I and 26.6, 24.9 and 12.4% for group II. The mean difference in peak torque was significantly greater at the low test speed (60°/sec) than at the high speed (180°/sec). At the last follow-up, the mean relative peak torque deficit for plantar flexion was 3.5, 5.3 and 1.4% at 60, 120, and 180°/sec, respectively, for group I and 6.6, 7.8 and 3.6% for group II (table 2).

The isokinetic calf muscle scores at the last control checkup were excellent in 56% of cases, good in 32%, fair in 8% and poor in 4% in group I, whereas the scores in the early motion group were excellent in 29% of cases, good in 50% and fair in 21% ($p = 0.17$, table 1). However excellent results were more common in early motion group ($p=0.08$).

Average Work (AW). The mean relative average work (J) differences between the normal and injured legs in plantar flexion were 3.5, 5.2, and 1.4% at 60, 120 and 180°/sec, respectively, for group I and 32.0, 26.6 and 19.2% for group II at the 3-month check-up and 8.8, 8.2, and 10.4% at 60, 120 and 180°/sec for group I and 7.9, 9.0, and 7.5% for group II at the last check-up (table 2).

Isometric strength. The mean relative isometric strength (Nm) deficit in the injured limb in plantar flexion at the 3-month check-up was 25.2% for group I and 24.1% for group II, the differences being statistically significant within the two groups ($p<0.001$) whereas the mean percentage strength difference between the groups was not significant. The mean relative strength deficit at the last checkup was 14.4% for group I ($p=0.057$) and 5.6% for group II ($p<0.001$, table 2).

Overall result. The ankle performance scores at the last control visit were excellent or good in 88% of cases in group I, fair in 4% and poor in 8% , whereas the scores in group II were excellent or good in 92% of cases and fair in 8% ($p = 0.85$, table 1).

Complications. The major complications included one deep infection and 3 re-ruptures, affecting three patients in all. The re-ruptures occurred a mean of 5 (range 3-7) months after the primary operation, one in group I and two in group II. One re-rupture was operated on with Lynn's plasty, and the isokinetic strength score and overall outcome were good at the last control visit. The deep infection plus re-rupture in another patient required two microvascular reconstructions, which failed, and the Achilles tendon was lost. The isokinetic calf muscle score at the last check-up was fair and the overall outcome poor. The third re-rupture was re-sutured, but the patient was lost from the follow-up because he moved abroad. According to the questionnaire sent to him, the musculotendinous unit was painless and not stiff and the subjective end result was good. There was still some moderate subjective calf muscle weakness in recreational activities, but not in everyday movement.

Table 1. Results at the last follow-up evaluation.

Clinical factor	Group I (Early motion) N= 25	Group II (Cast) N= 25	Overall Series N= 50		Statistical significance
Pain					>0.99
None	21	21	42	(84%)	
Mild, no limitations on recreational activities	3	3	6	(12%)	
Moderate, limitations on recreational, but not daily activities	1	1	2	(4%)	
Severe, limitations on recreational and daily activities	0	0	0		
Stiffness					0.087
None	21	17	28	(56%)	
Mild, occasional, no limitations on recreational activities	3	8	22	(44%)	
Moderate, limitations on recreational but not daily activities	1	0	0		
Severe, limitations on recreational and daily activities	0	0	0		
Calf muscle weakness (subjective)					0.774
None	19	19	38	(76%)	
Mild, no limitations on recreational activities	4	5	9	(18%)	
Moderate, limitations on recreational but not daily activities	1	1	2	(4%)	
Severe, limitations on recreational and daily activities	1	0	1	(2%)	
Footwear restrictions					0.096
None	17	23	40	(80%)	
Mild, most shoes tolerated	7	2	9	(18%)	
Moderate, unable to tolerate fashionable shoes, modified shoes tolerated	1	0	1	(2%)	
Active ROM difference between ankles					0.773
Normal (≤ 5°)	18	19	37	(74%)	
Mild (6°-10°)	5	4	9	(18%)	
Moderate (11°-15°)	1	1	2	(4%)	
Severe(≥16°)	1	0	2	(2%)	
(Missing data)*		1	1	(2%)	
Subjective result					0.060
Very satisfied	13	19	32	(64%)	
Satisfied with minor reservations	11	4	15	(30%)	
Satisfied with major reservations	0	2	2	(4%)	
Dissatisfied	1	0	1	(2%)	
Isokinetic muscle strength (score)					0.080
Excellent	14	7	21	(42%)	
Others	11	17	28	(58%)	
Ankle performance score					0.846
Excellent	15	15	30	(60%)	
Good	7	7	14	(28%)	
Fair	1	2	3	(6%)	
Poor	2	0	2	(4%)	
(Missing data)*		1	1	(2%)	

* missing data = one patient living abroad

Table 2. Mean (SD) peak torques (Nm) of plantar flexion and dorsiflexion of the ankles at velocities of 60°/sec, 120°/sec, and 180°/sec, mean average work (J) of the plantar flexion of the ankles at the same velocities, and mean isometric strength of plantar flexion in patient groups I and II at the last follow-up.

Group I (early motion, n=25)						Group II (cast, n = 24)				
Test speed	Injured Mean (SD)	Uninjured Mean (SD)	%- difference Mean (SD)	P-value	95% CI	Injured Mean (SD)	Uninjured Mean (SD)	%- difference Mean (SD)	P-value	95% CI
Peak torque										
Plantar flexion										
60°/sec	109.2 (33.2)	115.2 (28.4)	3.5 (15.6)	0.129	-3.1, 10.1	103.0 (21.6)	110.9 (22.7)	6.6 (11.6)	0.006	1.7, 11.5
120°/sec	80.2 (23.1)	86.6 (22.5)	5.3 (16.2)	0.040	-1.6, 12.1	76.0 (14.6)	84.2 (19.6)	7.8 (13.4)	0.001	2.2, 13.5
180°/sec	64.5 (15.0)	66.8 (15.7)	1.4 (13.9)	0.229	-4.5, 7.2	62.2 (11.1)	65.1 (12.6)	3.6 (11.2)	0.049	-1.1, 8.4
Dorsiflexion										
60°/sec	32.6 (6.9)	30.3 (7.3)	-9.8 (23.5)	0.030	-19.7, 0.2	28.3 (5.9)	27.2 (5.4)	-5.7 (22.9)	0.347	-15.3, 4.0
120°/sec	25.5 (5.1)	23.6 (1.1)	-9.9 (26.8)	0.047	-21.2, 1.5	22.4 (4.3)	22.0 (3.7)	-2.8 (16.9)	0.616	-9.9, 4.3
180°/sec	23.9 (4.3)	22.6 (5.0)	-7.3 (20.8)	0.054	-16.2, 1.4	21.9 (3.9)	21.4(3.6)	-2.8 (12.8)	0.417	-8.2, 2.6
Average work										
Plantar flexion										
60°/sec	63.6 (21.9)	70.7 (18.7)	8.8 (16.1)	0.008	2.0, 15.6	61.8 (12.8)	68.4 (15.9)	7.9 (14.9)	0.006	1.6, 14.2
120°/sec	48.0 (15.8)	53.5 (14.8)	8.2 (16.4)	0.007	1.3, 15.1	45.6 (7.8)	51.9 (12.9)	9.0 (16.6)	0.002	1.9, 16.0
180°/sec	37.3 (11.2)	42.4 (10.9)	10.4 (15.9)	0.001	3.7, 17.1	37.5 (7.7)	41.3(9.8)	7.5 (14.4)	0.005	1.5, 13.6
Isometric strength										
Plantar flexion	119.5 (45.8)	144.6 (41.4)	14.4 (19.5)	0.001	6.2, 22.6	123.7 (33.0)	133.0 (34.4)	5.6 (17.3)	0.057	-1.7, 12.9

5.2 AT elongation and isokinetic calf muscle strength (II)

AT elongation occurred to a lesser extent in the early motion group than in the cast group (p= 0.054 at mean 60 weeks). The curves increased significantly up to six weeks in both groups, however, and were not biphasic in either. The median AT elongation was 1.0 mm (25^{th} and 75^{th} percentiles -1.0–7.0) in group I and 4.5 mm (2.0-8.0) in group II at 1 week, 5.0 mm (2.0–9.0) in group I and 8.0 mm (4.0-10.0) in group II at 3 weeks, and 7.0 mm (2.0-14.5) in group I and 7.5 mm (5.5-13.0) in group II at 6 weeks (Fig. 9).

After six weeks the AT shortened somewhat in both groups, the median difference with respect to the starting point being 4.0 mm (-1.5–8.5) in group I and 5.0 mm (4.0–12.0) in group II at 24 weeks and 2.0 mm (-2.0–5.5) in group I and 5.0 mm (2.0–10.0) in group II at a mean of 60 weeks.

AT elongation correlated significantly with the clinical outcome (= -0.42, p=0.017), the patients with less AT elongation achieving a better clinical outcome, but not with age, body mass index or isokinetic peak torque values. The ankle performance scores were excellent or good in 88% of the patients in group I at the last control visit, fair in 4% and poor in 8%, whereas the scores in group II were excellent or good in 92% of cases and fair in 8% (p = 0.85). The isokinetic calf muscle scores at the last check-up were excellent in 56% of the patients in group I,good in 32%, fair in 8% and poor in 4%, whereas the scores in the cast group were excellent in 29% of cases, good in 50% and fair in 21% (p = 0.17).

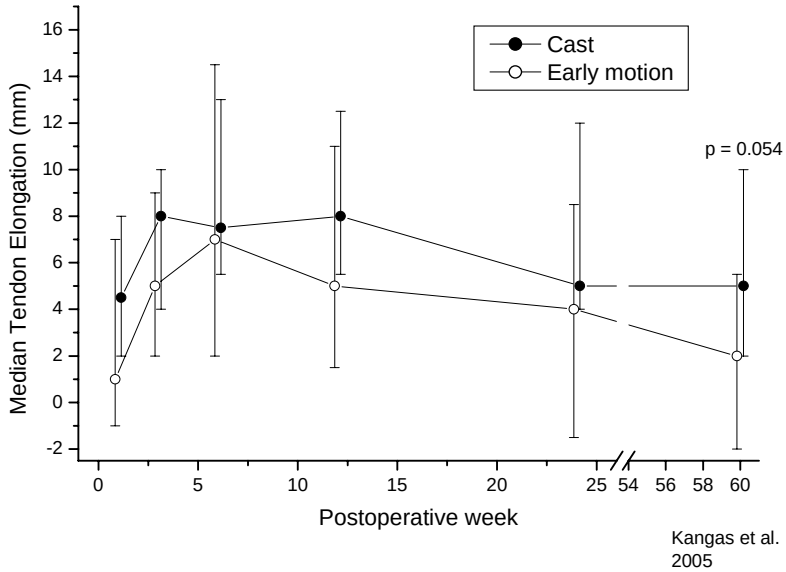


Fig. 9. Achilles tendon elongation.

5.3 Motor performance after ATR repair (III)

The results of the motor performance tests showed that there were no statistically significant differences in reaction times, speed of movement, tapping speed or coordination between the mean values for the operated leg and non-operated leg in either group three months or six months after the operation.

The differences between the groups in reaction times, speed of movement, tapping speed and anterior-posterior direction coordination on either side were not statistically significant three months after the operation, but the lateral direction coordination value of for operated leg was higher in the plaster group than in the splint group ($p<0.05$). Six months after the operation this single difference had disappeared ($p=0.6$).

There were no statistically significant changes between the values obtained three months after the operation and six months after the operation in either group (Table 3).

Table 3. Motor performance results for the operated and non-operated lower extremities in the patient (n = 90) group and for the control (n = 90) group mean SD.

Measurement	Unit	Patients		p (between sides)	Controls	p (between groups)
		Operated side	Nonoperated side		Side corresponding to the operated side	
Simple reation time	msec	233 (25)	234 (21)	0.651	236 (28)	0.422
2-choice reation time	msec	335 (46)	334 (42)	0.976	339 (50)	0.666
Speed of movement	cmsec	173 (48)	178 (49)	0.088	184 (53)	0.118
Tapping speed	taps/sec	5.32 (0.90)	5.36 (0.93)	0.579	5.13 (0.88)	0.098
Coordination	bits/sec	5.76 (1.13)	5.89 (1.09)	0.184	5.63 (1.06)	0.439

5.4 Strength properties of PLDLA 96/4 and polyglyconate (Maxon®) sutures (IV)

The mean initial tensile strength of non-sterile (non--irradiated) PLDLA was 577 (SD 20.3) MPa, that of g-irradiated PLDLA was 424 (SD 15.3) MPa and that of Maxon® was 697 (SD 57.5) MPa. The strength of Maxon in vitro at 0–2 weeks was significantly higher than that of the PLDLA sutures, but at 4 and 6 weeks PLDLA had significantly better strength properties. After 8 weeks of immersion in saline the tensile strength of Maxon® was not measurable, while that of the PLDLA sutures was 277 (SD 21.1) MPa. Finally, at 26 weeks the PLDLA sutures had a tensile strength of 23 (SD 9.3) MPa. The tensile strength of subcutaneously implanted Maxon® sutures *in vivo* was no longer measurable by 6 weeks, while that of PLDLA sutures was 318 (SD 53.6) MPa. Comparison of strength loss in vivo and in vitro showed a difference of 71.0 (95% CI 132 to 9.95) for Maxon sutures at 4 weeks.

The maximum force that could be applied to tendons repaired using either Maxon® or PLDLA sutures after one week showed no statistically significant difference, but after 2 weeks the breaking force required for tendons repaired using Maxon® was significantly lower than when using PLDLA sutures ($p = 0.029$).The Maxon®-repaired tendons with-

stood significantly higher maximum force at four weeks, however ($p = 0.029$), and by six weeks no statistically significant difference was found. When the maximum forces that could be exerted on the repaired tendons were related in each case to the intact controls (PLDLA-repaired tendon relative to control tendon compared with Maxon-repaired tendon relative to control), the only difference (almost significant; $p = 0.057$) was observed at 2 weeks. Otherwise there were no significant differences between the tendons repaired with these two materials in terms of breaking strength. Calculations of the percentage elongation of the repaired and control tendons revealed a significant difference was seen between the PLDLA-repaired and Maxon-repaired tendons at 4 weeks ($p = 0.029$).

5.5 Histological characterisation of PLDLA 96/4 sutures (V)

No skin irritation, tumours or other adverse effects were observed during the follow-up period. It was not possible to analyse all the samples, since not all the sutures were located inside the gastrocnemius tendon, but 8 samples, 5 with PLDLA (NM 60, NM = number of measurement points) and 3 with Maxon® (NM 36), were available at 2 weeks, 6 samples, 4 with PLDLA (NM 48) and 2 with Maxon® (NM 24) at 6 weeks, and 6 samples, 4 with PLDLA (NM 48) and 2 with Maxon® (NM 24) representing the final follow-up at 12 weeks.

The median thickness of the fibrous tissue capsule around the PLDLA sutures was 5.26 µm at two weeks, 11.66 µm at six weeks and 10.63 µm at twelve weeks, while that around the Maxon® sutures was 13.22 µm at two weeks, 80.97 µm at six weeks and 17.59 µm at twelve weeks. The Mann-Whitney test showed a significant difference in the thickness of the fibrous tissue capsule between the PLDLA and control (Maxon®) sutures ($p<0.01$).

Histologically, the suture materials were equally birefringent at 12 weeks as at 2 weeks, and total bioabsorption of the material had not yet taken place. Both materials seemed to initiate a mild inflammatory reaction, which was strongest at six weeks, that induced by Maxon® being clearly the stronger. No accumulation of any specific cell types in any great amounts could be observed. By the end of the experiment both suture materials were surrounded by thin collagen membranes, indicating good tissue reactions and a decrease in inflammatory responses.

6 Discussion

6.1 Early postoperative AT immobilization in tension vs. early functional treatment

The major finding was that the isokinetic calf muscle strength results were somewhat better in the early motion group, while the other outcome results were very similar between the two groups. This is the first published comparison of these two postoperative regimens.

The methodological quality of the investigation lies in its prospective, randomized design and the homogeneous groups of patients. The groups were adequately described and did not differ significantly with respect to gender, age, body mass index, activity level or previous Achilles tendon symptoms. The care programmes were identical in both groups, except for the immobilization method.

The outcome criteria included a previously published functional scoring system designed to measure isokinetic calf muscle strength and a questionnaire sent to the patients to be completed independently. Footwear restrictions, subjective outcome and objective factors such as the range of active ankle motion and isokinetic calf muscle strength were taken into account. The clinical observers were not blinded to the treatment groups. Only one randomized patient was lost from the clinical control. One limitation was the small number of patients in the series, which reduced the statistical power of the data.

The outcome results show that it is not necessary to use complicated suture techniques which rely on mechanically strong stitches, as the tendons were successfully repaired with the two modified Kessler suture technique using absorbable PDS® (polydioxanone) 2-0 gauge sutures and smaller apposition Vicryl® sutures, together with a central gastrocnemius aponeurosis flap, as proposed by Silfverskiöld (1941), that was turned down over the suture line and stitched to the Achilles tendon with Vicryl®.

The isokinetic muscle strength scores at the last control visit were excellent in 56% of the cases in the early motion group, whereas the scores in the cast group were excellent 29%. Thus no significant differences were detected between the groups at either the 3-month or final check-up. The performance scores in both groups were better than in the

series of Leppilahti *et al*. (1998), where the postoperative treatment consisted of 6 weeks of below-knee cast immobilization with the ankle in an equinus position for 3 weeks and in a neutral position for 3 weeks, allowing gradual weight bearing after three weeks, for which the scores were excellent or good in 79% of the 101 cases, fair in 17%, and poor in 4% a mean of 3 years postoperatively. Part of reason for our better results may lie in the homogeneous patient groups, because patients over 60 years of age, patients with systemic diseases and patients with late Achilles tendon ruptures were excluded from the present series.

The isokinetic calf muscle strength results were somewhat better in the early motion group, being excellent or good in 88% at the last check-up, fair in 8% and poor in 4%, whereas the scores after immobilization in tension were excellent or good in 79% of cases and fair in 21%. Again the results in both groups were better than those reported by Leppilahti (1996), where the isokinetic strength scores were excellent or good in 71% of cases, fair in 18% and poor in 11%. Previous reports on operatively treated ATRs followed by 6 to 8 weeks of cast immobilization of the ankle in an equine position have shown a mean isokinetic plantar flexion peak torque deficit of over 10% (Leppilahti *et al.* 1998, Inglis & Sculco 1981, Shields *et al.* 1978), whereas recent accounts of early functional postoperative treatment have quoted deficits of only 1 to 8% Carter *et al*. 1992, Mandelbaum *et al*. 1995, Saw *et al*. 1993, Speck & Klaue 1998, Troop *et al*. 1995). The present average peak torque deficit values were under 8% in both groups, i.e. comparable to previous results following early motion postoperative treatment.

The rate of major complications was 8%, comprising one deep infection (2%) and 3 re-ruptures (6%), and affecting three patients. The re-rupture rate is higher than the figures of 21/742 or 3.5%, for surgical treatment reported in the review by Khan *et al*. (2005). Re-rupture was preceded by a new trauma in each case. As the re-ruptures occurred a mean of 5 (range 3-7) months after the primary operation, it cannot be said that more substantial or more prolonged protection would have been necessary. It is not known whether these re-ruptures could have been avoided by the primary use of strong non-absorbable sutures. In any case, the outcomes consisted of one excellent result, one subjectively good one and one poor outcome caused by a deep infection and loss of the Achilles tendon.

The isokinetic calf muscle strength results were somewhat better in the early motion group, while the other outcome results were quite similar between the two groups of patients. We recommend early functional postoperative treatment after Achilles rupture repair for athletes and well motivated patients, and also for less motivated patients and non-athletes. Further prospective randomized trials are nevertheless evidently needed with regard to augmentation and non-augmentation techniques and the role of early full weight bearing in functional postoperative treatment.

6.2 AT elongation and isokinetic calf muscle strength

The major finding was that significant AT elongation occurred in both groups but was somewhat less marked in the early motion group. AT elongation correlated significantly with the clinical outcome, in that the less elongation occurred, the better were the out-

come scores, but it did not correlate with isokinetic calf muscle strength values, age or body mass index.

Elongation increased up to six weeks in both groups, but the rise was somewhat steeper in the cast group. After six weeks the AT preserved its length or even shortened a little in the early motion group. This shortening of the tendon between 24 and 60 weeks in the early motion group has not been mentioned in any earlier report. There are some conceivable reasons why this should happen, however. The primary mechanical strength of the tendon is dependent upon the extracellular formation of triple helix collagen fibrils with stabilizing molecular cross-links (Kadler *et al*. 1996) which takes place in this postoperative period. As the Achilles tendon descends, its fibres rotate by up to 90 degrees, with the posterior gastrocnemius tendon fibres rotating anterolaterally and the anterior soleus fibres running posteromedially (Cummins *et al*. 1946). It is also possible that both may re-rotate at that time and make the tendon shorter.

The causes of AT elongation may be numerous. Technical causes can include failure of the suture material, slipping of the knot or necrosis around the sutures which allows one of them to cut through the tendon. Mortensen *et al*. (1999) reported in a controlled study that 8 weeks of early restrictive postoperative treatment led to a mean tendon elongation of 9 mm at six weeks and 11.5mm at 12 weeks, while 8 weeks of postoperative cast treatment with the ankle in the equine position for 6 weeks and in the neutral position for 2 weeks led to a mean elongation of 5 mm at 6 weeks and 9 mm at 12 weeks. We found here that early separation was greater in the cast group, where the ankle was immobilized in tension in a neutral position for six weeks, while in the early motion group the tension was perhaps more appropriate and thus only minor tendon elongation occurred.

There were no selection, performance or detection biases in the present series. The clinical outcome measures included a standardized scoring system (Leppilahti *et al*. 1998), and the patients were asked to complete a written questionnaire independently.

One limitation was the small number of patients in the series, which reduced the statistical power of the data. Thus although the AT elongation curve was somewhat lower in the early motion group than in the immobilization group, this and other important clinical differences may be obscured by the lack of statistical significance. The use of intra-tendinous metallic markers may result in a source of error, although no loosening of the markers was found at follow-up. Another possible source of error may be variations in the ankle position in the radiographs. To eliminate this, a standardized brace was used and the ankle was fixed in the plantigrade position in all cases.

Although AT elongation occurred significantly in both groups, it was somewhat less marked in the early motion group. It also correlated significantly with the clinical outcome scores. We recommend early functional postoperative treatment after Achilles rupture repair.

6.3 Motor performance after ATR repair

It had been assumed at the planning phase that the results of the motor performance tests would be poorer in the plaster cast group (reaction times higher) than in the active brace

group, and also poorer three months than six months after the operation in both groups. No such effects were observed, however, and the results were in some respects surprising.

The finding that there was no difference between the operated and non-operated side in either group three months after the operation was especially disconcerting. Since the immobilization period after the operation undoubtedly reduces the activation level and range of motion in the joints (Leppilahti *et al*. 1996) and causes muscular atrophy in a plastered or braced leg (Häggmark & Eriksson 1979), we hypothesised that this may affect the movements or movement patterns achievable with this leg, but no such effect was observed. The precise reason for this finding is unknown, but it may be that the immobilization period reduces the activation level of whole body and thus also affects the performance of non-operated leg. Another reason could be that the active brace and the 90o position of the ankle joint during plastering successfully prevent these negative effects of immobilization and accelerate the recovery of performance after the immobilization period. Short muscle length during the immobilization period tends to increase muscle atrophy, and a stretched position delays this trend (Rantanen *et al.* 1993).

The differences between the groups in reaction times, speed of movement, tapping speed and anterior-posterior direction coordination on either side were not statistically significant either three or six months after the operation. The only exception was noticed in the lateral direction coordination test three months after the operation, where the value for the operated leg was higher in the plaster group than in the splint group, but this difference had disappeared six months after the operation. Caution is needed when attempting to draw definite conclusions on the basis of this result, however, as the finding differs markedly from the tendency visible in the other results and could be purely a matter of coincidence.

It seems in the light of these results that the recovery of some motor performance functions of the leg, as indicated by reaction times, speed of movement, tapping speed and coordination, does not depend on whether the leg is in plaster or in a brace during the immobilization period after Achilles tendon rupture repair. In addition, these motor functions have evidently recovered to the level of the non-operated leg by three months after the operation. It should be noted, however, that the total recovery and the possibility for resuming sports activities, for example, do not solely depend on these aspects of recovery, as factors such as muscle strength and range of motion may be even more important aspects. In addition, we used standard tests, and as these were performed in a sitting position (the anti-post coordination test was performed standing, but the subject was allowed to lean on a support), there was no loading on the AT during them. This fact slightly complicates any generalization of the results to a situation where the AT and the calf muscles are working under a load. In such cases the results could be different from those obtained here.

6.4 Strength properties of PLDLA 96/4 and Maxon® sutures

The differences in the initial tensile strength and strength retention of PLDLA and Maxon® sutures are due to differences in their manufacturing processes and the chemical structures of the raw material. One additional point was that g-irradiation was used to

sterilize the PLDLA sutures to avoid the toxic effects associated with using ethylene oxide residuals, since dry heat, autoclaving and g-radiation are known to cause degradation of polymeric materials (Vert *et al*. 1981, Gilding & Reed 1979). Tensile strength is the force applied per unit original cross-sectional area to a test specimen at any given time (Milch 1965). The initial tensile strength of non-sterile (non -irradiated) PLA filaments fell from 577.4 6 ± 20.3 MPa to 424 ± 15.3 MPa when they were -irradiated. Gamma-irradiation breaks the long chains of the polymer. Despite the fall in initial strength, PLDLA sutures still retain high strength values over time, which is an advantage that could be demonstrated in this study. Since Maxon® was found to lose its strength *in vivo* in 6 weeks; we limited our follow-up of the operated tendons to this length of time. The PLDLA-repaired and Maxon®-repaired tendons nevertheless showed comparable results.

Some previous investigators have observed accelerated strength loss of PLA *in vivo* relative to the situation *in vitro*, probably due to enzymatic action (Vasenius *et al.* 1990), while others have reported no differences between the rates of degradation of PLDLA 96/4 in vivo and in vitro (Saikku-Bäkstöm *et al*. 1999). Enzymes have been found to affect PLA degradation when tested in vitro (Williams 1981), but no significant difference in the strength loss of PLDLA sutures *in vivo* and *in vitro* was observed in the present work. Similarly, no significant strength loss was seen at 1–2 weeks when Maxon sutures were used *in vivo*, but the tensile strength was higher *in vivo* than i*n vitro* at 4 weeks, probably due to a difference in the initial strength of the Maxon sutures used, because by 6 weeks Maxon still had a strength of 30 MPa i*n vitro*, whereas *in vivo* it had lost its strength completely. The overall trend thus showed lower values *in vivo*. Maxon is a copolymer of glycolide and trimethylene carbonate (polyglyconate) (Rosensaft & Webb 1981), and the initiation of hydrolysis in polyglycolide has been found elsewhere to be faster *in vivo* than *in vitro*, due to the effect of enzymes (Williams 1979), but we did not observe such an effect in the present experiments.

This principle was applied here to calculate the tensile strength of sutures tested *in vitro* and *in vivo*. As regards repaired tendons, the healing tendon specimens retrieved were of various thicknesses, but the cross-sectional area measurements were ignored and only the values for the maximum force before breaking are indicated. The breaking strengths of the repaired tendons reflect the strength of the re-formed collagenous fibrous structure and the suture complex.

The mechanical strength of a given degradable polymer and its strength retention in a hydrolytic environment and in living tissues are affected by several factors (Vainionpää *et al*. 1989), such as its chemical composition, impurities, molecular orientation, matrix reinforcement morphology, porosity, surface quality, size, geometry, surface area, tissue environment, molecular weight (Törmälä *et al.* 1991) and crystallinity. The degradation rate also depends on the size of the implant (Grizzi *et al*. 1995). Degradation of copolymers such as PLDLA is thought to be faster than that of homopolymers such as PLLA, and this can be exploited to avoid unnecessarily retention times of foreign bodies in tissues. Although PLDLA has an initial tensile strength which is lower than that of Maxon®, it retains its strength over a longer period, giving more prolonged support to a healing weak tendon.

When considering clinical applications, the use of PLDLA sutures with prolonged strength retention would be advantageous in human subjects, where Achilles tendon healing is thought to be slower than in growing rabbits. As observed in the present study, the

tensile strength properties of PLDLA are comparable to those of Maxon sutures, and hence there is a choice of using either of these absorbable sutures for Achilles tendon repair. Maxon had lost its strength at six weeks, while that of PLDLA was still over 300 MPa. In clinical practice, a repaired Achilles tendon is immobilized in a cast for 3–6 weeks, a which point it is mobilized. At this stage distraction forces start to act on the repaired tendon, and hence, strong sutures have a role to play in the prevention of tendon wound disruption. We may speculate that the use of a suture material such as PLDLA, with relatively prolonged strength retention properties, would be advantageous for the simple reason that it provides support after the cast is removed, that is at the time of mobilization.

6.5 Histological characterisation of PLDLA 96/4 sutures

It has been shown previously that upon the implantation of bioabsorbable materials a fibro-inflammatory tissue forms due to the stimulation of a local inflammatory response and the activation of fibroblasts, which deposit layers of collagen around individual fibres or particles of the degrading implants. It is also important to evaluate these sutures in terms of the tissue reactions they induce both spatially and temporally.

This first study of the biocompatibility of PLDLA 96/4 implanted inside tendon tissue indicates that implant fibres do not undergo total bioabsorption. In fact, no histological signs of biodegradation could be seen at 12 weeks, since the implant fibres were just as birefringent as they had been at 2 weeks and no implant material was noted in macrophages or other cells. Experiments with other types of tissue show that total bioabsorption of similar PLDLA fibres takes more than one year when implanted in minipigs for joint replacement purposes (Waris *et al*. 2004) or episclerally in rabbits (Länsman *et al.* 2005).

In the collagen matrix area of the tendon the material seemed to be very inert, and a very thin capsule of both materials was measured in that specific section during the follow-up period of 12 weeks in the present experiments. This may have been due to the relative avascularity of the collagen matrix area of the tendon, since the cells in a local inflammatory reaction are recruited from the circulating blood. The decrease in the thickness of the fibro-inflammatory reaction seen with Maxon between 6 weeks and 12 weeks could be explained by maturation of the connective tissue. As the tissue reaction continues around any foreign material, some maturing and organization of the connective tissue occurs, reducing its volume. In fact, the tissue reaction around bioabsorbable materials continues until biodegradation is complete. This experimental study was limited to the first 12 weeks, because this is the period of greatest interest in the healing process of Achilles tendon ruptures, most re-ruptures being reported to occur during the first 3 months (Pajala *et al*. 2002) and any adverse reactions during this time, such as an inflammatory reaction within the tendon tissue, could affect the healing process in a harmful way.

The use of bioabsorbable sutures with prolonged strength retention properties is advantageous for the simple reason that they can provide support for the healing tendon and also reduce the risk of long-term complications. Polylactides do not interfere with MRI or CT examinations, and they are totally bioabsorbed by natural pathways

(Ashammakhi *et al.* 2004). The PLDLA used here has an initial tensile strength of 424 MPa and it retains 42% of this initial strength for 13 weeks, thus degrading at a slower rate than a Maxon® suture of same diameter. The present intratendinous PLDLA sutures formed a thinner fibrous capsule at 12 weeks than did the Maxon® sutures, and there was no tension or other biomechanical stress on the material caused by knotting, for example, because the aim was to study the tissue reactions to the material itself. In order to avoid any discrepancies, the material was inserted intratendinously into the unaffected AT. In this way the results are easier to compare, without individual differences that could be caused by variability in the size of the experimental tendon lesions, efficiency of haemostasis or the size and location of knots, for example. The basic reaction to the material itself provides essential information needed for determining the possible advantages or disadvantages of the technique. According to this preliminary study, PLDLA is a promising suture material that can be used for the operative repair of Achilles tendon ruptures.

7 Conclusions

The isokinetic calf muscle strength results were somewhat better in the early motion group, while the other outcome results obtained in the two groups of patients were very similar. Early functional treatment after Achilles rupture repair can be recommended for postoperative treatment method.

AT elongation was somewhat less in the early motion group and correlated with the clinical outcome scores. Early functional postoperative treatment after Achilles rupture repair is thus also recommendable than immobilisation in tension by cast.

In the light of the present results, it seems that the recovery of motor performance functions in the leg does not depend on whether it is in a plaster cast or an active brace during the immobilization period after Achilles tendon rupture repair. In addition, these motor functions of the operated leg have evidently already recovered to the level of the non-operated leg 12 weeks after the operation.

There was no significant difference between the *in vitro* and *in vivo* tensile strength retention of PLDLA sutures. By comparison with Maxon®, PLDLA was found to have a lower initial tensile strength but more prolonged strength retention. The breaking strength values of the Achilles tendons repaired with sutures of these types were not significantly different at 6 weeks.

Intratendinous PLDLA sutures formed a thinner fibrous capsule during the 12-week follow-up period than did Maxon® sutures of the same diameter. The suture materials had not been totally absorbed by 12 weeks.

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Original publications

This thesis is based on the following articles referred to the text by their Roman numerals:

I Kangas J, Pajala A, Siira P, Hämäläinen M & Leppilahti J (2003) Early immobilization in tension vs. early functional treatment of the musculotendinous unit after Achilles rupture repair. J Trauma 54:1171–1181.

II Kangas J, Pajala A, Ohtonen P & Leppilahti J (2007) Achilles tendon elongation after rupture repair. A randomized comparison of two postoperative regimens. Am J Sports Med 35:59–64.

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V Kangas J, Pajala A, Leppilahti J, Ashammakhi N, J, Törmälä P & Waris T (2006) Histomorphometric analysis of poly-L/D-lactide 96/4 sutures in the gastrocnemius tendon of rabbits. Int J Artif Organs 29:893–899.

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