Achilles Tendon Rupture:
The evaluation and outcome of percutaneous and minimally-invasive repair

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Wendoline Ramsbottom: Yer dog's waiting.
Wallace: Aye, I'd better see to him. The bounce has gone from his bungee.
Wallace and Gromit: A Close Shave, 1995, Bob Baker & Nick Park

Abstract

Acute Achilles tendon rupture is common and has increasing incidence. This is thought to be due to increasing activity and sports participation in middle age. Sustaining an Achilles tendon rupture means a long rehabilitation period and many patients do not achieve full recovery of strength and function. One of the reasons for this reduced function is considered to be due to tendon elongation.

The reasons for the lack of recovery have been discussed in earlier studies comparing operative and non-operative treatments. Operative treatment can be divided into open, minimally-invasive and percutaneous technique. Proponents of operative treatment consider open technique to prevent tendon elongation and reduce the re-rupture rate, compared with non-operative treatment. Percutaneous repair is considered to lead to a higher incidence of iatrogenic nerve damage and reduced repair strength compared with open repair, but is considered to be advantagous because of the lower risk of infections and wound problems.

The purpose of this thesis was to evaluate and optimise the outcome of percutaneous and minimally-invasive repair techniques for an Achilles tendon rupture. Moreover, evaluation instruments were developed and an already existing validated questionnaire was culturally adapted in English to be used in the United Kingdom.

Achilles Tendon Resting Angle (ATRA) is an indirect measure of tendon elongation. The method has been developed and validated in one of the studies. ATRA has subsequently been used to evaluate the clinical outcomes. The ATRA angle increases after an Achilles tendon rupture, then decreases after operative intervention to finally increase again during the first rehabilitation phase. The ATRA angle was shown to correlate with patient-reported outcomes and function as measured by heel rise height one year after injury. Thus, ATRA can provide an indication of function achieved after treatment of an Achilles tendon rupture.

Achilles Tendon Total Rupture Score (ATRS) is a validated patient-reported questionnaire for evaluating limitations and physical activity after an Achilles tendon rupture. ATRS was

originally developed for a Swedish population, but has now been translated and culturally adapted to an English population. ATRS has also been used for evaluating patient-reported outcomes.

Percutaneous and minimally-invasive surgical techniques have been evaluated in 169 patients treated for an Achilles tendon rupture. Percutaneous technique was found to be more cost-effective in comparison to open procedure, with similar results regarding function and patient-reported symptoms. Minimally-invasive repairs produced similar outcome to percutaneous repair but with a lower complication rate. Based on these results, minimally-invasive repair is recommended for the operative treatment of an acute Achilles tendon rupture.

In order to compare the strength of different suture materials after repair of the Achilles tendon, a cadaveric study was performed, in which the tendon was cyclically loaded. The result from this study shows that repair with non-absorbable suture has better strength in comparison to a absorbable one.

However, there is still a lack of knowledge of why a patient suffering from an Achilles tendon rupture does not fully recover. Further studies involving how treatment and rehabilitation can be optimised is of value.

Keywords: *Achilles tendon rupture, percutaneous, minimally-invasive, outcome, Achilles tendon Total Rupture Score, Achilles Tendon Resting Angle, Heel-Rise Height*

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Sammanfattning på svenskat

Akut hälseneruptur är vanligt förekommande och incidensen har ökat på senare år. Detta anses bero på ett ökat intresse att delta i idrottsaktiviteter allt högre upp i åldrarna. Att drabbas av en hälseneruptur innebär en lång konvalescens och många får kvarstående besvär med främst nedsatt muskelstyrka. En av anledningarna till den nedsatta funktionen anses bero på att hälsenan läkt med en förlängning, som ett ”utdraget gummiband”. Orsaken till den uteblivna återhämtningen har diskuterats i många studier, där ofta operativ och icke-operativ behandling har jämförts. Den operativa behandlingen kan delas in i öppen ”mini-invasiv”, och perkutan teknik. Dessa olika behandlingsmetoder har sparsamt utvärderats i jämförelse med varandra. Förespråkare för operativ behandling anser att öppen teknik kan förebygga senförlängning och minska antalet re-rupturer, det vill säga att senan går av igen, jämfört med icke-operativ behandling. Perkutan reparation av hälsenan anses, jämfört med den öppna tekniken, ge fler nervskador och sämre muskelstyrka, men anses vara en fördel med lägre antal infektioner och sårproblem jämfört med öppen teknik.

Syftet med denna avhandling var att göra en kostnadsanalys, utvärdera och optimera resultaten efter perkutan respektive ”mini-invasiv” teknik, vid behandling av hälseneruptur. Vidare att utveckla utvärderingsinstrument och kulturellt anpassa befintligt validerat frågeformulär.

Achilles Tendon Resting Angle (ATRA) är ett indirekt mått på senförlängning. Metoden har utvecklats och validerats för att därefter användas vid utvärdering av den i avhandlingen ingående kliniska studien. ATRA-vinkeln ökar efter att hälsenan gått av, minskar sedan efter operativ intervention för att sedan öka igen under rehabiliteringsfasen. ATRA-vinkeln har visat sig korrelera med patient-relaterat utfall och funktion som uppmätts med tåhävningshöjd ett år efter skada. ATRA kan därmed ge en indikation om uppnådd funktion efter behandling av hälseneruptur. Achilles Tendon Total Rupture Score (ATRS) är ett validerat patient-relaterat frågeformulär för utvärdering av besvärsnivå efter behandling av akut hälseneruptur. Formuläret är ursprungligen

utvecklat för en svensk population, men har nu i en av studierna översatts och kulturellt anpassats till en engelsk population. ATRS har också använts för utvärdering av patient-relaterat utfall i den kliniska studien. Perkutan och ”mini-invasiv” operativ teknik har utvärderats på 169 patienter som behandlats för akut hälseneruptur. Perkutan teknik visade sig, vara mer kostnadseffektiv i jämförelse med öppen teknik. ”Mini-invasiv” och perkutan teknik hade i övrigt likvärdiga slutresultat avseende funktion och patient-relaterade symtom. Med bakgrund av detta resultat förordas perkutan teknik för behandling av akut hälseneruptur.

För att jämföra olika suturmaterials hållfasthet efter reparation av hälseneruptur gjordes en kadaverstudie där senan belastades cykliskt. Resultatet från denna studie visar att reparation med icke-resorberbar sutur har en bättre hållfasthet i jämförelse med en resorberbar.

Det saknas fortfarande kunskap om bakomliggande orsaker till varför en patient som drabbas av en hälseneruptur inte blir fullt återställd efter behandling. Fler studier som undersöker hur behandling och rehabilitering kan optimeras är av värde.

List of Papers

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

I. *Carmont MR, Silbernagel KG, Nilsson-Helander K, Mei-Dan O, Karlsson J, Maffulli N.* Cross cultural adaptation of the Achilles tendon Total Rupture Score with reliability, validity and responsiveness evaluation. Knee Surg Sports Traumatol Arthrosc 2013;21(6):1356-1360.

II. *Carmont MR, Heaver C, Pradhan A, Mei-Dan O, Grävare Silbernagel K.* Surgical Repair of the ruptured Achilles tendon: the cost effectiveness of open versus percutaneous repair. Knee Surg Sports Traumatol Arthrosc 2013;21(6):1361-1368.

III. *Carmont MR, Silbernagel KG, Edge A, Mei-Dan O, Karlsson J, Maffulli N.* Functional Outcome of Percutaneous Achilles Repair: improvements in Achilles Tendon Total Rupture Score during the first year. Orthop J Sports Med 2013;1(1):325967113494584

IV. *Carmont MR, Grävare Silbernagel K, Mathy A, Mulji Y, Karlsson J, Maffulli N.* Reliability of Achilles Tendon Resting Angle and Calf Circumference measurement techniques. Foot Ankle Surg. 2013:19(4):245-249.

V. *Carmont MR, Grävare Silbernagel K, Brorsson A, Olsson N, Maffulli N, Karlsson J.* The Achilles tendon resting angle as an indirect measure of Achilles tendon length following rupture, repair and rehabilitation. Sports Med Arthros Rehab Tech 2015;2:49-55.

VI. *Carmont MR, Zellers JA, Brorsson A, Olsson N, Nilsson-Helander K, Karlsson J, Grävare Silbernagel K.* The functional outcome of Achilles tendon minimally-invasive repair using 4- and 6-strand nonabsorbable suture. Orthop J Sports Med 2017 5(8):2325967117723347.

VII. *Carmont MR, Kuiper JH, Grävare Silbernagel K, Karlsson J, Nilsson-Helander K.* Tendon end separation with loading in Achilles tendon repair model: comparison of non-absorbable vs absorbable suture. J Exp Orthop 2017 4(1):26.

Additional Papers by the author on the same topic

Braunstein M, Baumbach S, Boecker W, Carmont MR, Polzer H. Development of an accelerated functional rehabilitation protocol following minimal invasive Achilles tendon repair. Knee Surg Sports Traumatol Arthrosc 2015 ahead of print DOI: 10.1007//s00167-015-3795-1.

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Carmont MR, Highland AM, Blundell CM, Davies MB. Simultaneous bilateral Achilles tendon ruptures associated with statin medication despite regular rock climbing exercise. Phy Ther Sport 2009;10(4):150-152.

Carmont MR, Maffulli N. Z shortening of healed Achilles tendon rupture: a technical note. Foot Ankle Int 2009;30(7):704-707.

Richards PJ, Braid JC, Carmont MR, Maffulli N. Achilles tendon ossification: pathology, imaging and aetiology. Disabil Rehabil 2008;30(20-22):1651-1665.

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Carmont MR, Maffulli N. Management of insertional Achilles tendinopathy through a Cincinnati incision. BMC Musculoskelet Disord 2007;15;8:82.

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Contents

Abbreviations

ADL	Activities of Daily Living
ATRA	Achilles Tendon Resting Angle
ATRS	Achilles tendon Total Rupture Score
BMI	Body Mass Index
BW	Body Weight
Drop CMJ	Drop Counter Movement Jump
HRH	Heel-Rise Height
HRR	Heel-Rise Repetition
ICC	Intraclass Correlation Coefficient
IQR	Inter-Quartile Range
J	Joule
LSI	Limb Symmetry Index
MRI	Magnetic Resonance Imaging
MDC	Minimal Detectable Change
N	Newton
Nm	Newton meter
PAS	Physical Activity Scale
PROM	Patient Reported Outcome Measure
PTFE	Polytetrafluoroethylene
RCT	Randomised Controlled Trial
SEM	Standard Error of Measurement
US	Ultrasound Imaging
USP	United States Pharmacopeia

Definitions in short

Achilles Tendon Resting Angle-Absolute	The acute angle between the long axis of the fibula and the line between the tip of the lateral malleolus and the centre of the fifth metatarsal head. Measured with the patient prone and the knee flexed to 90˚.
Achilles Tendon Resting Angle-Relative	The difference between the ATRA on the injured and the non-injured ankle.
Body Mass Index (BMI)	Weight(Kg)/Height(m)^2
Creep	The change in length of a tendon due to the prolonged application of a force.
Gapping	Incomplete tendon end-to-end apposition with management.
Hystersis	This is the alteration of changes of stiffness and length with the loading and unloading of a biological tissue. This is the ratio of dissipated to stored energy from a tendon when it is loaded and unloaded.
Mode of failure	This is the mechanism by which failure actually occurs. Rupture usually involves complete separation of the tendon ends
Minimally-invasive repair	Minimally-invasive repair is defined as the operative repair with direct visualisation of end-to-end tendon apposition. Sutures may be passed through additional incisions or tenocutaneously, passed directly through the skin.
Negative Predictive Value	The proportion of individuals with a negative test result that do not have the specific condition.
Open tendon repair	Open repair of the Achilles tendon is defined as any operative repair where all sutures are placed through the same operative incision.
Percutaneous repair	Percutaneous repair is defined as the operative maintenance of end-to-end apposition of the ruptured tendon ends. Tendon end-to-end apposition may be confirmed indirectly using the either intra-operative ultrasound or endoscopic visualisation. Sutures may be passed through additional incisions or tenocutaneously.
Positive Predictive Value	The proportion of individuals with a positive test result that have the specific condition.

Power	The product of force and contracion velocity, expressed as Newton meter/second (Nm/s) or Watt (W).
Resilience	The quality or energy applied to deform a tendon without resulting in permanent, or plastic deformation.
Sensitivity	The proportion of individuals with a condition that has a negative result in a specific test.
Separation	The separation of the tendon ends during management.
Specificity	The proportion of individuals without a condition that has a negative result in a specific test.
Strength	The amount of force that can be applied to a material of body. Measured in Newtons (N).
Tenocutaneous	The passage of a suture directly through the skin into or across the tendon, rather than through a stab incision.
Ultimate tensile strength	This is the highest force at which the tendon, or repair, will separate and rupture
Young's Modulus of elasticity/stiffness/ compliance	Is a measure of the stiffness of a material. This is the slope or gradient of the stress/Strain curve.
Viscoelasticity	This is the change in biomechanical properties with time over which the force is applied.
Work	The product of force and distance through which the body moves. Expressed in Joules (J) or Newton meter (Nm).

1. Introduction

Michael R Carmont

1.1 Mythology and history

Achilles was the hero of Homer's poem the Iliad. In Greek mythology Achilles was dipped into the river Styx by his mother Thetis to give him powers of invincibility. Thetis held onto Achilles by the tendon to his heel bone leaving him with a weak spot, giving the phrase the Achilles heel. Achilles was eventually slain by an arrow fired by Paris, the son of King Priam and Queen Hecuba of Troy. The arrow was guided by Apollo and struck Achilles in the heel. It is rumoured that the arrow was poisoned, although it is equally possible that the wound became infected leading to septicemia leading to his demise [9, 245].

Although previously known as the "tendo magnus of Hippocrates" in 1693; Philip Verheyen is considered the first to use the term the "Achilles" tendon [9].

The vulnerability and morbidity caused by pathologies of the Achilles tendon was recognised by Hippocrates "The Achilles tendon if bruised or cut causes the most acute fevers, induces choking deranges the mind and at length brings death."

1.2 Anatomy

The Achilles tendon links the gastrocnemius and goleus muscles to the calcaneus. The gastrocnemius muscle has two heads originating from the medial and lateral sides of the posterior femoral condyles [71]. The muscle fibers extend distally passing across the knee joint to merge with fibers of the soleus and form the Achilles tendon. The soleus muscle originates from the posterior aspect of the head and superior quarter of the fibula and the soleal line and middle third of the tibia on the medial side *(Figure 1)*.

The tendon passes distally and crosses both the ankle and subtalar joint. This means the gastrocsoleus and Achilles tendon complex spans 3 joints, with implications regarding its function. The Achilles tendon is comprised of different fascicles, from each of the muscles of the triceps surae, which externally rotate 90˚, to insert onto different facets of the calcaneus [21,83] *(Figure 2)*. The rotational nature of these fascicles and the arrangement of the facets contribute to the increased moment arms increasing the

effectiveness of muscular contraction [58]. There is a bursa, known as the retrocalcaneal bursa between the distal insertion and the posterior superior calcaneal tubercle. An additional bursa may form between the distal tendon and the skin known as the subcutaneous bursa [48].

The plantaris muscle, which is absent in 10%, originates from the posterior aspect of the lateral femoral condyle passes distally crossing to the medial side of the Achilles insertion on the calcaneus [69].

The Achilles tendon has no formal tendon sheath, but proximally it is covered by two discrete layers, the fascia cruris and the paratenon, which merge distally at 3cm from the Achilles insertion [47]. The fascia cruris is a tough fibrous layer, which acts as a conduit for the perfusing blood vessels [16]. The paratenon is a vascular layer through which the tendon receives the majority of its nutrition.

The tendon is typically 18cm long and 6mm in the anterior-posterior (AP) dimension [93,183,248].

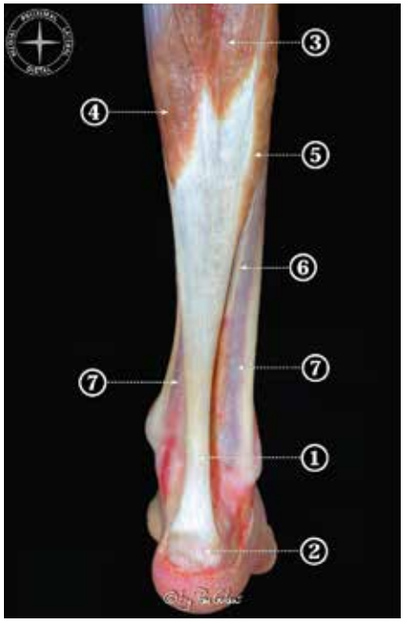


Figure 1. The musculotendionous complex of the Achilles tendon spans the knee, ankle and sub-talar joints. Reproduced with permission.

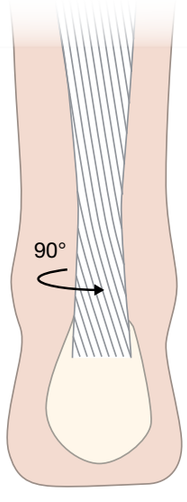


Figure 2. The 90˚ external rotation of the fibers corresponds with eversion in mid-stance and inversion with concentric muscular contraction in plantar flexion and toe off.

1. Structure of the tendon

The Achilles tendon develops from the epimysial fibers of the gastocnemius and soleus muscles forming a tendon. The tendon consists of fascicles, fibrils, sub-fibrils and microfibrils *(Figure 3)*. The microfibrils consist of collagen and elastin embedded within a proteoglycan matrix. The dry weight of the tendon is composed of 65-80% type I collagen, 0-15% type III collagen and 1-2% elastin [141, 224, 225].

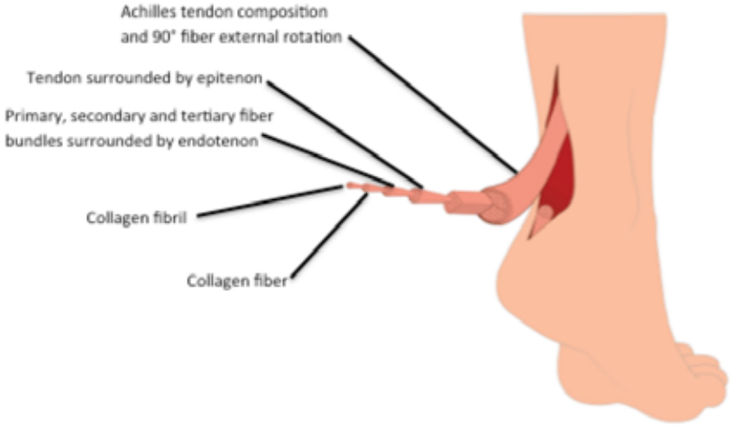


Figure 3. Tendon composition, leading to the formation of mop head strands of fiber bundles following rupture.

2. Circulation

The Achilles tendon and the paratenon are supplied by branches from two main arteries, the posterior tibial and the peroneal arteries [2,50,59,162]. The proximal musculotendinous and distal osseotendinous sections are relatively well perfused, supplied by the posterior tibial artery. The mid-section from the mesotenon, supplied by the peroneal artery is relatively hypovascular and this corresponds to the site of rupture. Digital vascular mapping of the integument, overlying layers has revealed a marginal vascular predominance with relative sparing of the central overlying structures [302]. There is additionally an intra-tendinous blood supply. The location and tenuous nature of the vascular supply has implications for surgical approach and wound healing. More recently the microcirculation of the tendon has been shown to correlate with healing and rehabilitation [241]. An improved combined patient reported and functional outcome at one year was significantly correlated with higher maximum blood flow ($r=0.777$, $p=0.04$) in the injured limb [241].

3. Innervation

The Achilles tendon is principally innervated from the epitenon with sensory branches forming the tibial and sural nerves. The paratenon also has Pacinian corpuscles suggesting the proprioceptive nature of this layer. The sensory innervation of the Achilles tendon has been extensively studied in relation to tendinopathy and the mid-portion of the tendon has multiple sympathetic and sensory nerves on the outside but not the inside of the ventral side of the tendon [10].

4. Metabolism

Tendons have previously been considered to be relatively inactive since they utilise 7.5 times less oxygen than skeletal muscle [224]. There is a balance between collagen synthesis and degradation. Synthesis activity is highest during growth and diminishes with age [225]. Levels of glucose and glutamate [102] and other essential metabolites as well as markers of tendon callus production, Procollagen I and III N-Terminal Peptide, may be determined using micro-dialysis techniques to determine healing at early stages following tendon rupture [286]. The degree and distribution of glucose uptake following a bout of exercise has also been used as a marker of tendon healing [85]. The measurement of glucose and other metabolic markers may be of value in future outcome assessments.

5. Biomechanics

In response to loading, the tendon elongates (2%) and the fibers align from their unloaded crimped position. With increased loading the tendon increases in length 2-6% deforming elastically. During this region of the curve if the load is withdrawn the tendon will relax, releasing energy. Beyond 6% elongation permanent plastic deformation will occur until the tendon fails beyond 8% strain [48] *(Figure 4)*. The ultimate tensile strength of fresh frozen Achilles tendon specimens has been determined to be 1189N (360-1965) [181].

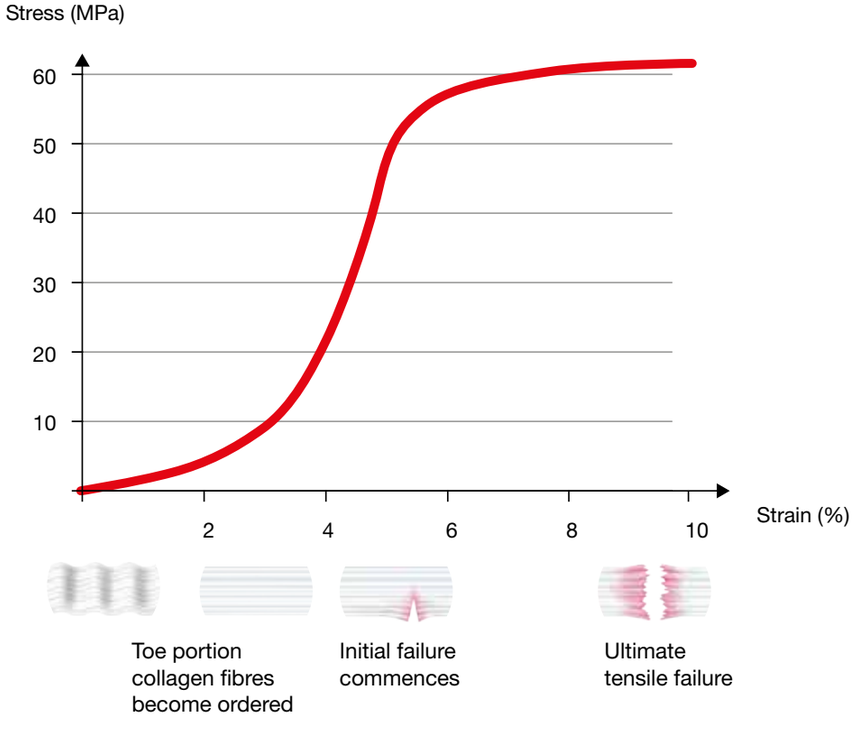


Figure 4. The biomechanical characteristic of the stress/strain curve for biological tissues. The increase in strain before ultimate tensile failure leads to the formation of the mop-head of the tendon ends.

The tendon's biomechanical properties vary according to its structural composition and its dimensions during the healing process. The radiodensity of the healing tendon, measured using CT scanning, has been shown to reflect the mechanical properties [252] and this in turn has been used to predict final outcome [254]. The modulus of elasticity has been determined at 188.56±99.19 MPa in healthy tendons [75]. Agres et al. determined that tendons repaired using a percutaneous Dresden technique, were stiffer 335.7±132.6 MPa, compared with non-injured tendons 198.6±34 MPa following 43.5 months of healing and rehabilitation [1]. Conversely, Geremi et al. at 1-2 years follow up, reported that during a maximal isometric force there was lower maximal stress and modulus of elasticity by 60% (effect size=3.457) and 58% (effect size=2.321) respectively between the injured, repaired using an open Kessler suture, compared with the non-injured tendon [97]. The changes of the mechanical properties that occur during tendon healing and rehabilitation are not completely understood. The aim of treatment of the ruptured Achilles tendon must be to restore the tendon's biomechanical properties to those of a normal healthy tendon. This thesis contributes to the research focusing on the restoration of the simplest variable, that of tendon length.

1.3 Rupture

1.3.1 Incidence

The incidence of Achilles tendon rupture has been increasing since the 1980s of 18 per 100,000 person years *(Table 1)* [173,186]. A much greater appreciation of variations in incidence has occurred with the adoption of nationwide hospital [126,165,198] and health-care provider databases [256,269,292] together with the development of Achilles tendon rupture registries [95]. A mean annual increase in rupture rate of 2.4% has been reported [165]. Although the mean age for Achilles tendon rupture is in the mid 40s, recently it has been appreciated that rates of increase vary according to age. The greatest increments have been reported in the over 60 age group, while the rate in the under 40 age group appears to be decreasing [126].

Table 1: The reported increasing incidence of Achilles tendon over time.

	Country	Year	Incidence per 100,000
Leppilahti [173]	Finland	1979-1986	2
		1987-1994	12
Maffulli [186]	Scotland	1981	4.7
		1994	6
Houshian [123]	Denmark	1984	18.2
		1996	37.3
Levi [175]	Denmark	1997	13.4
Suchak [269]	Canada	1998	5.5
		2002	9.9
Lantto [165]	Finland	2011	21.5 (2.4%pa)
Huttunen [126]	Sweden	2012	69
Ganestam [95]	Denmark	1994	27
		2013	31
Sheth [258]	Canada	2003	18
		2013	29.3

The typical age pattern has been considered to adopt a bimodal distribution [49,186,223] with a sports-related peak in the early 40s and another smaller peak in the 70s-80s age group *(Figure 5)*. The older age peak tends to sustain their injuries during day-by-day activities such as pushing cars, walking up or down stairs or as a result of a simple stumble [49,61].

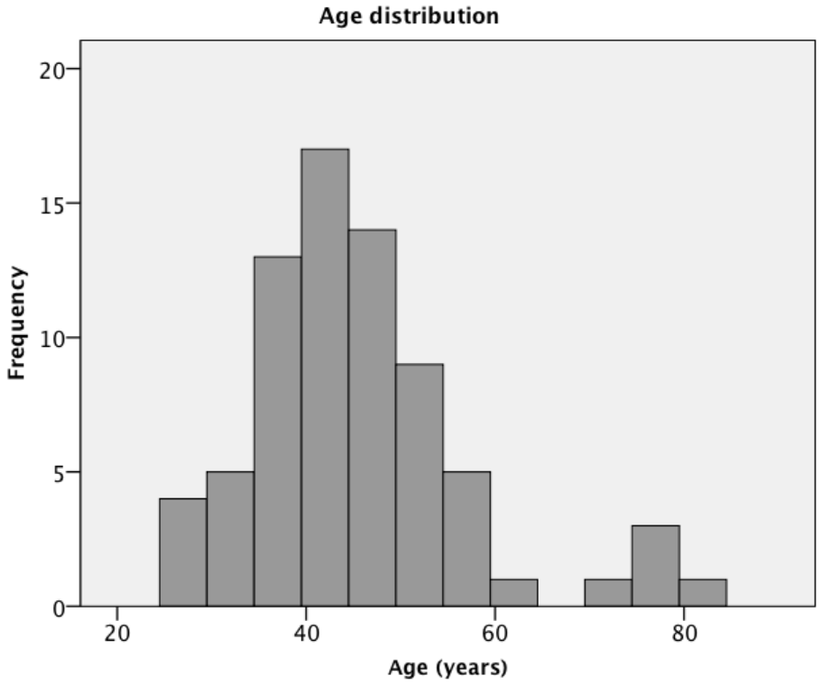


Figure 5: The bimodal distribution of Achilles tendon ruptures.

There is male predominance in the ratio of 3-4:1 [223,289]. Rates of 47 per 100,000 person years in males and 12 per 100,000 person years in females have been reported in 2012 [126].

There are conflicting findings in terms of seasonal variation of ruptures. A peak incidence in the spring and early summer could be explained by increased outdoor sports participation in the northern hemisphere [256]. Conversely a series from Denmark reported a seasonal peak in the autumn or fall [95].

1.3.2 Mechanism

The mechanism of injury is typically a rapid eccentric loading of the gastrocsoleus complex and additionally the change from an eccentric to a concentric force with a high peak load. This most commonly occurs during sports activity such as football, particularly 5-a-side and badminton for males and netball for females [49,61,136].

Additionally, a traumatic fall directly onto the forefoot, rather than the heel, resulting in forced ankle plantar flexion can also lead to rupture. These usually occur with a fall from a height with greater soft tissue, bone and joint trauma than that occurring during eccentric contraction.

Direct trauma is possible, but when this occurs with a sharp edge such as a glass or broken tile this tends to result in an open laceration [6,18,163,250].

The majority of tears occur during sports activity and histological analysis has found evidence of degeneration and inflammation at the rupture site [55,134,136,190]. Additionally ruptures tend to occur after following the recent return to sports after a period of absence. From these descriptions Achilles tendon ruptures could be considered to be fatigue or stress related; either a ”normal’ force applied to abnormal tendon, or an increased unaccustomed force applied to normal tendon. There is an almost 200 fold increase in the risk of contralateral tendon rupture in patients who have previously sustained a rupture [14].

1.3.3 Symptoms

The majority of patients with a rupture report feeling and hearing a pop and localise this to the midsubstance of their Achilles tendon. They commonly report feeling as though they have been struck from behind and frequently look around to see who their assailant is.

Patients may fall to the ground losing their balance with hyperflexion of the ankle. They subsequently will be able to bear weight on the affected limb and perform open kinetic chain plantar flexion, but not perform a single heel rise. In the presence of an Achilles tendon rupture, the other plantar flexors of the lower limb, predominantly tibialis posterior, flexor hallucis longus and flexor digitorum longus and peroneus longus and brevis can plantar flex the ankle. A previous history of local symptoms precedes rupture in 15-21% of patients [29,89,129].

1.3.4 Clinical signs and diagnostic tests.

The fascicular structure of the Achilles tendon and the mode of rupture of biological tissues, with rupture and elongation of the remaining fibers before they rupture, lead to the characteristic mop-head appearance of the ruptured tendon ends *(Figures 4 and 5)*. The most common site of the rupture is at 4-6cm from the Achilles insertion *(Table 2)* [267].

The majority of ruptures are transverse (63%) and occur through a relative hypovascular zone result in localised haematoma. The elongation during rupture may lead to oblique tears (37%) extending into the musculotendinous junction [55,267]. A tear in this vascular musculotendinous junction is considered to have more swollen calf than that occurring with a purely midsubstance intra-tendinous tear [262].

Table 2: The anatomical location of Achilles tendon ruptures [267].

Location	%	Number
Middle 1/3	50	32
Proximal 1/3	28	19
Proximal 1/3-Middle1/3	12	8
Distal 1/3	9	6
Proximal 2/3-Middle 1/3	1	1

Examination of the acutely ruptured Achilles tendon may reveal local swelling, a visible and palpable gap to the tendon. The medially located plantaris tendon may be intact; creating the impression of a partial rupture due to its intact fibers *(Figure 6)*.

Various clinical eponymous tests are described in the literature [262,263,264,281]. A passive dynamic test is the calf squeeze test [262,281]. This has been described by both Simmonds and Thompson and Doherty at roughly the same time point in papers and proceedings [262,265,281,]. The patient is positioned prone and the calf at the level of the soleus muscle is squeezed, avoiding pressing on the peroneal compartment. The squeeze increases the distance of the tendon from the tibia and this displacement causes the ankle to plantar flex if the tendon is intact [257]. These use the absence of a tenodesis effect of the tendon to indicate integrity or rupture. A positive test is when the ankle fails to plantar flex with calf compression *(Figure 7)* [265].

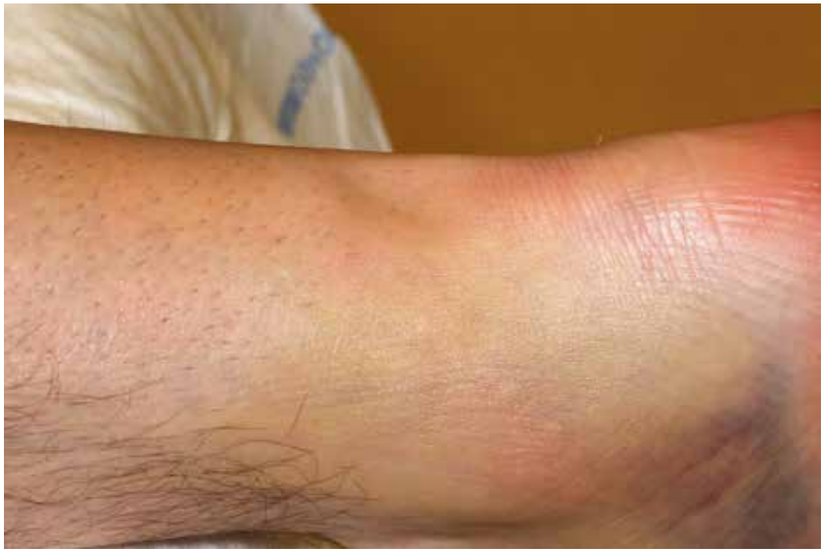
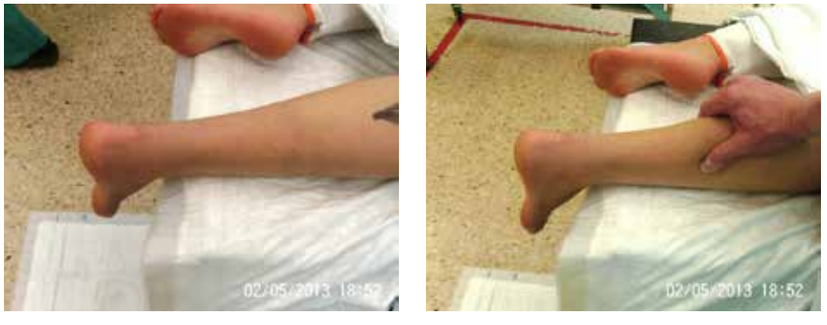


Figure 6: A palpable gap is present in the majority of mid-substance tears. The visible and palpable band on the medial side of gap is the plantaris tendon.



Figures 7: The calf squeeze test: in the figure squeezing on the calf does not alter the position of the ankle joint, indicating an Achilles tendon rupture, a positive test.

Matles' test is an observational dynamic test with the patient lying prone with knees extended and both feet over the end of the examination couch [197]. The patient flexes both knees to 90˚ and the position of the foot is observed. If the ankle adopts a neutral or dorsiflexed position the tendon is considered incontinuous or ruptured *(Figure 8)*.

The diagnostic value of these tests have been determined and the calf squeeze test and the Matles' test had the highest sensitivity (0.96 and 0.88 respectively) and specificity of (0.93 and 0.85 respectively) [185,247].

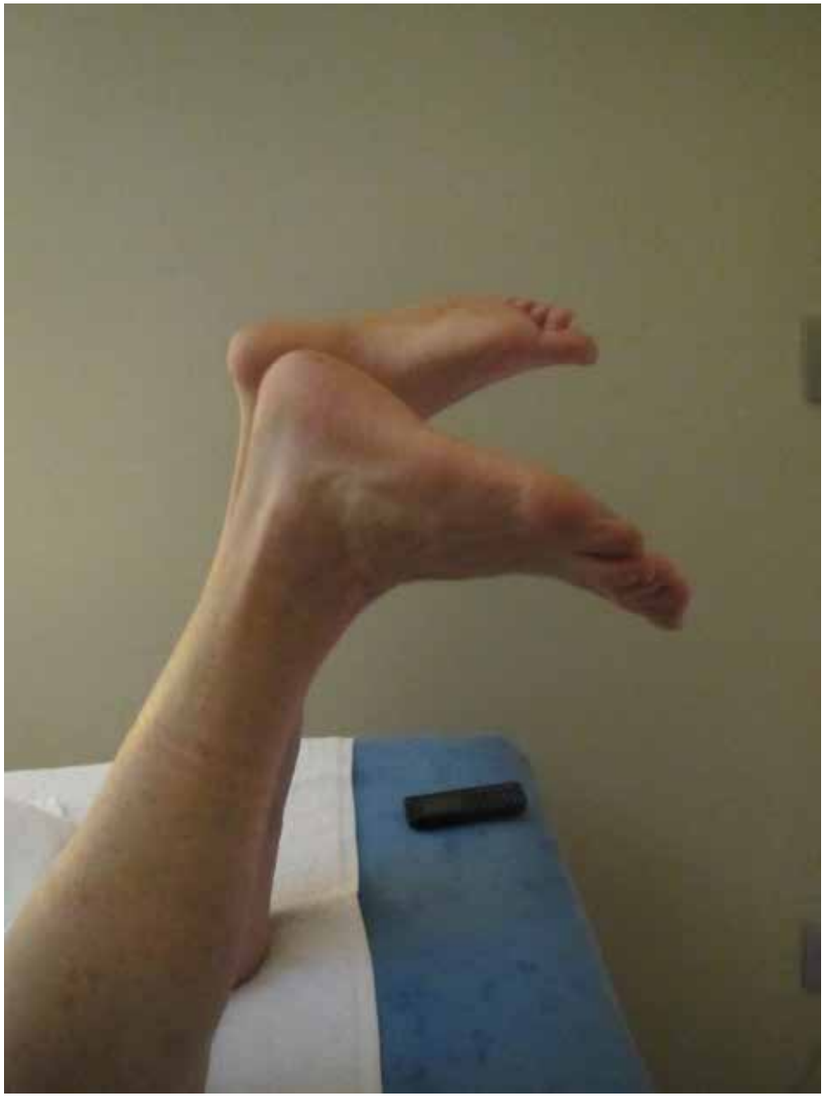


Figure 8: Flexion of the knee to 90˚ reveals increased dorsiflexion in the left ankle compared to the right, indicating an Achilles tendon rupture.

The importance of the palpable gap, calf squeeze and resting position tests in combination has recently been highlighted in general medical journals [263] and this article has been reproduced in the British Journal of Sports Medicine [264] in order to reduce the 1 in 5 neglected presentation rate [129]. The reasons that ruptures may not be detected at first presentation are usually related to atypical

presentations. Patients may present after injuries not associated with sport, they may think they have sustained an inversion injury to their ankle or may have co-morbidities e.g. diabetes, which alter the sensation of a typical rupture. The palpable gap may be misinterpreted as the fusiform swelling associated with Achilles tendinopathy and patients may be able to walk even in the presence of a rupture.

The proximal end of the rupture is less distinct than the distal stump, which becomes more prominent during increased ankle dorsiflexion. The gap may be more visible and appreciable in more distal ruptures. Ruptures within 2cm of the Achilles insertion may be more challenging to manage both operatively and non-operatively due to the amount of stump available for suture placement and a potential lack of tendon end apposition, or gaping, with non-operative management. With ruptures at this position the skin is pulled taught over the short stump and so it is easily palpable.

1.3.5 The role of imaging for diagnosis and determination of treatment

The use of imaging may be considered to establish the diagnosis of rupture, the extent of rupture, the location of rupture and to determine treatment options [43]. Magnetic Resonance Imaging produces digital images based upon imaging slices and separations between the slices [96]. Ultrasound scanning is operator-dependent and can be used to determine tendon end proximity [103,240].

A systematic review of 56 studies concerning ultrasound has recommended to rely primarily on clinical examination and evaluation and to use imaging for ruling out other injuries and to provide additional clinical information [72]. Separation of up to 10mm with passive ankle plantar flexion has been considered adequate for non-operative management [125,244,278,295]. Westin et al. have shown that patients with a diastasis of >10mm who were treated non-operatively had a higher risk of re-rupture ($p<0.001$). In non-operated patients there was a significantly worse outcome in patients with a diastasis >5mm in terms of patient-reported outcomes using the ATRS ($p=0.04$) and heel rise height ($p=0.048$) at 12 months compared with a group with a lesser degree of tendon end separation [295]. Lawrence et al. noted that patients, mean age 52 years, with a gap >10mm with the ankle in the neutral position had significantly greater peak torque deficit than those with gaps <10mm (mean 23.3%; 7% to 52% vs. 14.3% to 47%, $p=0.023$) [168]. Imaging may be useful to determine the location of the tear. The location of tears has an influence on outcomes in respect to whether the tear is in the mid-substance region or at the musculotendinous junction. Musculotendinous tears have been managed non-operatively, with 6 weeks of functional bracing with no re-ruptures being reported and Foot Ankle Ability Measure (FAAM) scores of 95 reported were after 40 weeks [2].

Since the introduction of Magnetic Resonance Imaging (MRI) in the 1980s, this modality has been increasingly used in the diagnosis and management of tendon ruptures [70,280]. The discrimination between a partial and a complete rupture may be difficult with the mop ends produced following rupture. Similarly the determination of true gapping is difficult and clinical examination has been shown to be more accurate in the diagnosis of Achilles tendon rupture than MRI [96]. The sensitivity of the MRI was 90.9%, whereas the presence of an abnormal Thompson test, decreased resting tension of the ankle and and palpable defect predicted a complete rupture in 100% patients. MRI therefore may not be a useful addition to management decision-making, but may be helpful during follow-up [93,208,246,293]. This can yield information in terms of tendon length and calf muscle bulk [248].

1.4 Management

1.4.1 Treatment Options

Management options for ruptures of the Achilles tendon can be broadly split into non-operative and operative treatment. The trend has varied between these two distinct treatment methods over time. In the 1930s Qeno and Stoianovitch stated ”Rupture of the Achilles tendon should be operated on without delay” [243]. However, the complications of surgery led Lea and Smith in 1968 [169] and 1972 [170] to state that ”Operative repair of Achilles tendon rupture is unnecessary” [169,170]. Meta-analyses comparing the differences in outcome between operative and non-operative management have produced differing recommendations based on the inclusion and exclusion criteria of the studies, the management methods used and the outcomes reported [30,88,121,132,154,155,179,202,266,296,298,299,307,309]. More recently studies by Nilsson-Helander et al. did not demonstrate a significant difference in patient-reported outcome between operative and non-operative treatment [218] and Willits et al. reported good outcome of non-operative treatment comparable to operative treatment [297]. With the introduction of early-accelerated rehabilitation rather than cast immobilisation, the trend has turned more towards non-operative management.

Barfod et al. surveyed Orthopaedic Departments in Scandinavia from October 2011 to October 2012 (93% response rate) [22]. Sixty-five percent of departments would recommend operative repair for healthy active people less than 50 years of age. Operative treatment was the treatment of choice for Danish, Norwegian and Swedish hospitals regardless of the increasing evidence for non-operative treatment. Although increasing evidence has favoured dynamic rehabilitation, allowing movement of the ankle after week 2, it has gained limited use across Scandinavia. Weight-bearing was used in most hospitals and surgery tended to be performed by junior surgeons [22].

Subsequently a decrease in the proportion of patients treated operatively has decreased between 2001 and 2012 in males from 43% to 28% and in females from 34% to 22% has been noted in Sweden [126].

Decreasing rates for operative repair have been reported in Finland [198]. In 1987 rates for surgery were 11.1 and 2.5 per 100,000 person years for males and females respectively [198]. These have increased to 20.5 and 4.2 per 100,000 person years respectively in 2011. Rates peaked in 2008 for males and 2007 for females prior to the publication of Nilsson-Helander et al. and Willits et al. [218,297]. Since then the rate of operative treatment has decreased to 55% in women and 42% in men [198].

1.4.2 Non-operative management

Non-operative management encompasses a wide range of different aspects of weight-bearing and ankle movement comprising rehabilitation following injury. Traditional practice has been to avoid weight-bearing and movement with a below-the-knee cast for 6 weeks, followed by the gradual restoration of ankle motion in plaster and serial cast application until the 12 week time point.

As knowledge has advanced, the practices of less conservative, post-operative rehabilitation regimes with early weight-bearing and early movement have been applied to non-operative treatment regimes [23]. This accelerated rehabilitation [149,150] has shown similar re-rupture rates compared with operative treatment [266]. The use of an equinus cast has decreased and more patients are using functional braces. These, as the name suggests, allow the angle of immobilisation of the ankle to be changed without repeated cast applications [290]. Other forms of bracing allow the limb to bear weight using a supportive Bohler iron [304]. This iron is attached to either side of a circumferntial cast around the calf. This permits some ankle range of movement but no loading across the injured tendon.

One of the largest reported series (n=945) on the managment of Achilles tendon rupture comes from Northern Ireland [291]. Here the population has been almost exclusively managed non-operatively since 1996. Following initial non-weight bearing in a cast, the patient is permitted to weight bear using a pneumatic walker with heel wedges from 2 weeks. Over the next 6 weeks the wedges are sequentially removed until the patient is fully weight-bearing before a final assessment at 14 weeks. Good to excellent subjective assessment on discharge was noted in 939 patients (99.4%; 943 tendons). A re-rupture rate of 2.9% was reported. Patients are discharged at 14 weeks when satisfactory plantar flexion strength, according to the patient’s own perception of strength and function, has been re-gained.

A recent study has, however, shown when weight-bearing in a boot with wedges to achieve ankle plantar flexion that much of this flexion actually occurs at the midfoot joints rather than the ankle joint [86].

Achilles rupture management programmes

have used a Vacoped walker boot (OPED GMbH Oberlaindern, Germany), an angled ankle brace with a vacuum liner. Once the angle is set, the air is sucked out of the liner so that it conforms to the ankle joint. This boot also has a rocker sole to promote a normal walking motion. This permits full weight-bearing with supportive protection against further injury and re-ruptures. Large case series (n=211) have shown the use of the brace provides satisfactory outcomes ATRS 72.4 at 9 months following rupture and low re-rupture rates (1.1%). The boot is initially set at 30˚ plantar flexion and this angle is reduced to 15˚ and finally to 0˚ over a 5 week period. After this, the boot is worn for at risk activities for up to 4 months following injury [125].

Similarly a 17 year experience of 114 patients followed up for a minimum of one year has been reported with a mean Thermann score of 82 points [84]. Patients were placed into a semi-rigid soft cast in 20˚ of equinus and whilst this cured patients stood on a 20˚ wedge. Patients were then weight-bearing in the cast using a Rehabilitation boot. The cast was removed at the 6 week time point and wedges were sequentially removed and exchanged from the boot every two weeks until the patient was weight-bearing flat on the ground at 12 weeks [84].

In both of these management pathways, patients were examined using ultrasonography and clinically using a resting angle to determine the presence of tendon gaping.

Surveys of clinicians have revealed wide variations in clinical practice for non-operative treatment. In 2010 Osarumwense et al. received replies from 86 out of 221 consultants surveyed [235]. Seventy-two percent treated Achilles tendon rupture non-operatively with 82% using below knee casts, 5.8% using above knee casts and 7% using functional braces. These respondents were general orthopaedic surgeons (n=24) as well as foot and ankle specialists (n=38). The specialists tended to use a shorter period of immobilisation with a median of 8(3-13) weeks compared with 9(6-36) weeks for the general orthopaedic surgeons. Both groups tended to make patients non-weight-bearing for 6 weeks following injury [235]. By contrast an online survey of members of the British Orthopaedic Foot and Ankle Society revealed 13% cast alone, 68% cast followed by orthotic management and orthosis alone 19%. Out of those using orthosis, 55% used a rigid rocker and 42% used a Controlled Ankle Motion (CAM) orthosis [151].

More recently further variations in practice have been identified from German Orthopaedic and Trauma institutions with patients being maintained with fixed plantar flexion for longer after non-operative treatment compared with operative repair 3.6±0.1 weeks vs. 47±0.3 weeks respectively. Patients were similarly protected to neutral for 5.8±0.1 and 6.6±0.2 weeks [92].

1.4.3 Operative management

Operative management may be generally divided into open, minimally-invasive and percutaneous repairs. Post-operative management also has a key role in the patient-reported outcome following Achilles tendon rupture.

1.4.3.1 Open repair

Open repairs of the Achilles tendon can be defined as any operative repair, where all sutures are placed through the same surgical incision. Open repairs have the advantages that all of the ruptured tendon can be seen directly, sutures placed in macroscopically normal tendon and repaired through the incision. This allows the visual confirmation that the ruptured tendon ends are apposed, permits locking sutures to be easily inserted and a running circumferential suture to be applied [230]. In Olsson et al's. randomised controlled trial (RCT) there were no (0%) re-ruptures in patients repaired using a two Kessler sutures and a Silfverskiold circumferential running suture [230]. Although the size of incisions may be minimised to 2.5-4cm [277], techniques in which all sutures placed within the tendon are inserted through the single incision are termed open.

Additionally an open technique permits the repair to be augmented by fascial turn-down flaps [238] and free flaps [216]. It must be borne in mind that this method of augmentation showed no difference in outcome when compared with simple repair in either early 12 months [239] or long term

(14 years) [114] follow-up. Outcomes were 79% and 90% excellent or good respectively. The technique showed no impact on strength and there was no improvement in calf muscle strength between 12 months and 14 years. Notably elongation occurred in both groups with a mean of 14.5mm in the augmented group but only 12.7mm in the simple repair group.

Similarly the use of a plantaris weave was considered to give worse outcomes when used with an end-to-end repair using Krackow sutures. At 17.8 months patients reported similar AOFAS scores of 96.7 and 98.8 respectively. It is clinically relevant, however, not statistically significant that there were greater numbers of complications using the augmented repair [5].

Meta-analyses have shown that end-to-end repairs have equal outcome scores, compared with primary repairs augmented with a fascial turn down flap [308]. The use of the flap does not prevent tendon lengthening or muscle weakness [114,238]. Augmented repairs may be reserved for repairs of chronic ruptures and re-ruptures [216].

Disadvantages of open repair include the risk of infection, delayed wound healing, even wound breakdown *(Figure 9)*, and adhesions [169]. If infection and wound breakdown occurs wounds may take up to 18 months to completely heal [39,237].

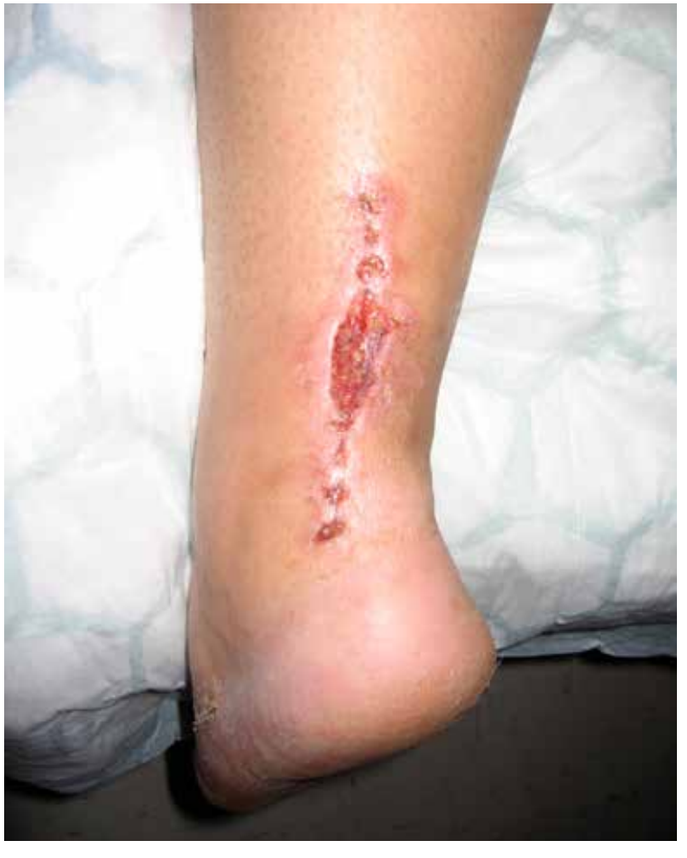
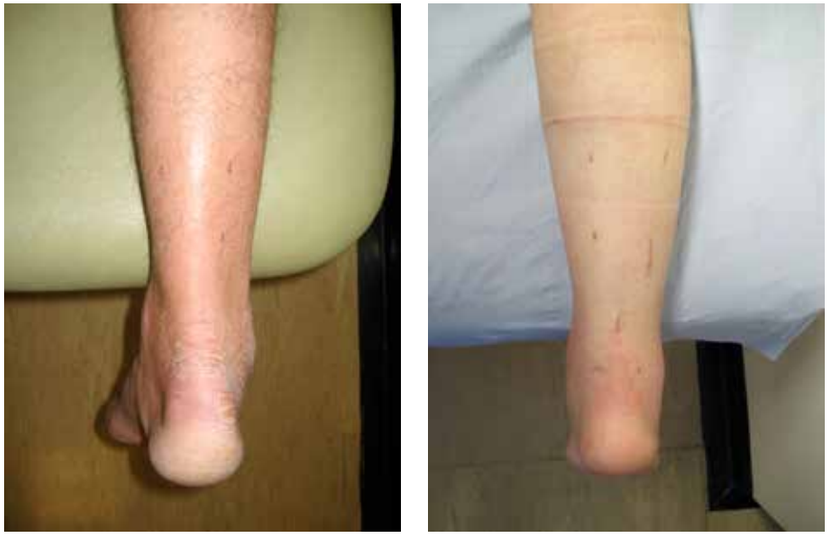


Figure 9: Wound breakdown and poor wound healing at 12 months following an open repair.

Percutaneous and Minimally-invasive repair

Advantages of percutaneous and minimally-invasive repair are the reduced risks of wound problems and improved cosmesis compared to open repair *(Figure 10)*. The terminology between a percutaneous and minimally-invasive repair has become blurred. In this thesis percutaneous repair is defined as the operative maintenance of an end-to-end apposition of the ruptured tendon ends. End-to-end apposition may be confirmed using the either intra-operative ultrasound [161,268] or endoscopic visualisation [56,60,80,111,273]. Minimally-invasive repair may be defined as the operative repair with direct visualisation of end-to-end tendon apposition. Sutures may be placed either via an incision at the rupture site or separate incisions in both techniques. A separate incision placed for knot tying is still considered to be a percutaneous repair technique.



Figures 10: The reduced risk of wound problems and improved cosmesis offered by percutaneous and minimally invasive repair.

Percutaneous repair of the Achilles tendon permits the tendon ends to be apposed together using sutures placed through stab incisions only. This allows sutures to be placed into the Achilles tendon proximally and distally to the rupture site. Small incisions may be placed at the rupture site for knot tying [46].

Percutaneous repair:

The classical percutaneous technique was described by Ma and Griffiths in 1977 [182]. This comprises a Bunnell suture proximally and a box suture distally with a mass suture tie next to the rupture site *(Figure 11)* [182]. No re-ruptures were recorded in 18 patients, in most patients a small non-tender nodule was present consistent with the subcutaneous suture knot [182].

The risks of this technique include iatrogenic injury to the sural nerve, either by knot compression or suture transfixation [119]. The symptoms of paraesthesia usually settle with time particularly if absorbable sutures are used and the sural nerve is visualised, mobilised and protected [157,158,193]. Additional disadvantages include comparative weakness (50%) of the repair configuration, with increased dorsiflexion during biomechanical testing [57,119] and an increased re-rupture rate [34].

To reduce the rates of knot prominence and adhesions sutures and surgical knots may be placed either within the tendon; intra-tendinous [46], alongside the tendon; paratendinous [15,31,40,66,160] or proximally; distant from the rupture site [8,107,153].

The use of the Dresden Instrument is a ring device inserted proximally and used to retrieve tenocutaneous sutures from the distal stump bypassing the rupture site [8,107,153]. This may allow the knot to be covered by additional subcutaneous tissue found proximally. Additionally the skin, fascia cruris and paratenon remain intact at the rupture site.

Knowledge of the course of the sural nerve and midline mattress suture placement minimises the risk of sural nerve injury *(Figure 11)* [52,53,67,294].

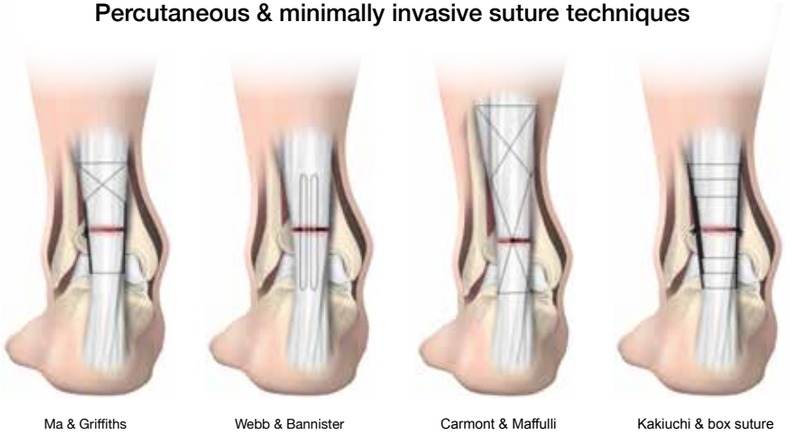


Figure 11: Percutaneous and minimally-invasive suture techniques.

Minimally-invasive repair:

Kakiuchi et al. in 1994 described a combined repair technique in which looped Kirschner (K)-wires were inserted through a skin incision at the rupture site [138] *(Figure 11)*. This allowed sutures placed across the tendon to be retrieved through a surgical incision over the rupture site and direct visualisation of end-to-end tendon apposition *(Figure 12)* [138]. This terminology encompasses the "percutaneous" variations of this technique where surgical instruments, e.g. Rampley's or ring forceps [87,143,214], arthroscopy hooks [236,239], and jigs, notably the Achillon jig devised by Assal et al. [15,59,127,201,203] have been inserted through an incision at the rupture site to form either a box suture or transtendinous locked suture with individual or mass paratendinous suture knots *(Figure 11)*. An incision of approximately 2-4cm long is required to insert the jig and ensure the branches are on either side of the tendon and within the paratenon. It is possible to penetrate the fascia during the jig placement [16].

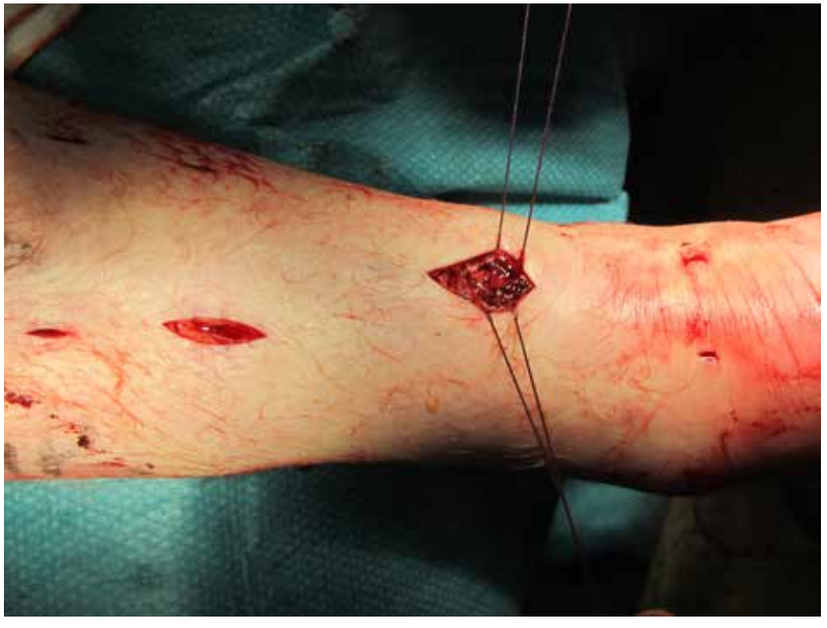


Figure 12: Minimally-invasive repair of Achilles tendon rupture allows direct visualisation of end-to-end tendon apposition.

The tenocutaneous placement of sutures through guide holes in the branches enables the sutures and pull-through sutures to be inserted into the tendon. After withdrawal from the surgical incision careful looping of the sutures and pull-through sutures enables locked sutures within the proximal and distal tendon to be enclosed within the crural fascia. This incision does allow semi-circumferential running sutures to be applied to the apposed tendon ends increasing repair strength.

The blind passage of tenocutaneous sutures places the nearby subcutaneous, and extra fascial, sural nerve at risk of injury. This injury is likely to be a needle stab and neuropraxia related to suture passage. Given that sutures may be temporarily placed through the nerve, means that symptoms are likely to be transient. The incorporation of the nerve within a knot is unlikely. The jigs may be rotated to minimise nerve injury [3] and sophisticated methods of suture positioning may minimise the number of knots used [26].

Minimally-invasive and percutaneous surgery for the Achilles tendon rupture aims to provide a stable repair, allowing early weight-bearing and movement, whilst minimising the risks of wound breakdown or infection [77,135,202,301].

The use of a combined modified Bunnell and Kessler suture configuration [46] *(Figure 11)* using an absorbable monofilament suture shows good clinical outcome in general [7,49] as well as in specific patient subsets; such as athletes [192], elderly [189] and diabetic patients [191]. This suture technique has similar repair strength to that of the box suture created using the Achillon device [180].

Although monofilament absorbable sutures e.g. polyglyconate co-polymer Maxon (Covidien, Mansfield, MA, USA) are broken down over six weeks, which may potentially avoid stress shielding *(Table 4)*, the associated inflammatory response may in fact weaken the healing tendon predisposing to re-rupture at a key phase in the rehabilitation process. Braided non-absorbable sutures made from polyester coated with a polytetrafluoroethylene (PTFE) layer (Fiberwire®, Arthrex, Naples, USA) are commonly used for Achilles tendon repair [74,127,153]. The sutures offer the advantages of strength, smooth passage through the tendon and secure knots [27]. An increased number of core suture strands has been shown to increase the strength of suture repair models [19,234] but this has not been studied using combined modified Bunnell or Kessler configurations. The increased number of strands and increased suture thicknesss may increase the pull-out strength or ultimate tensile failure.

Post-operative management:

In the post-operative period initial concerns are related to wound healing and in particular the presence of infection and wound breakdown. A temporary post-operative plaster back or front shell, with a period of non-weight-bearing may be considered for wound protection for open repairs [54,152,210,218,219,284,297].

The use of percutaneous and minimally-invasive techniques has reduced healing complications related to the wound [51,124,200]. Confidence in repair techniques has permitted early and immediate weight-bearing [187,188,239] and early mobilisation [188] and systematic literature studies consider these to be safe and also offer superior outcome [35].

A meta-analysis of randomised and quasi-randomised trials, revealed 6 studies that administered a combined early weight-bearing (within 2 weeks of repair) and early ankle motion exercise (within 2 weeks of repair) programme and 3 studies that used active or early passive motion exercises only without weight-bearing [38,51,124,200,288]. Most outcomes were significantly better for patients who underwent early weight-bearing and ankle motion exercises than for those who underwent cast immobilisation. This included a shorter time to return to sports activity ($p<0.0001$), greater heel rise ability ($p=0.05$) and achievement of normal ankle range of motion ($p=0.03$). Patients who underwent early ankle motion exercises without early weight-bearing did not have significantly different ankle range of motion or strength compared with those who were immobilised. There was no difference in re-rupture rate or complications [38,51,124,200,288]. McCormack and Bovard reported that patient outcomes were better in the bracing group for good and excellent results ($p=0.01$; OR 3.13 95% CI 1.3 to 7.53) in favour of functional rehabilitation at 6-12 weeks after operative repair [200].

A systematic review studying at the rehabilitation following percutaneous and minimally invasive repairs has shown that immediate weight-bearing using a brace and early mobilisation is safe and offers superior outcome [35].

1.4.4 Imaging during management

Although imaging has been shown to be less sensitive than clinical examination [72,96,185], the use of ultrasound is still of value in managing Achilles tendon ruptures, particularly in terms of the location and extent of tendon gap separation. It is also of clinical value to determine when operative repair is needed, or when non-operative treatment is likely to fail [84,125,295].

Intra-operative ultrasound has benefits of confirming the location of the tear, confirming intra-tendinous suture/wire placement and finally end-to-end tendon apposition.

One of the benefits of an open or minimally-invasive repair is that this allows the surgeon to see the sutures within the tendon substance. The Amlang technique places a transcutaneous and transtendinous suture across the distal stump and retrieves this through a proximal incision and locked to the proximal tendon [8]. The ”Harpoon” technique developed by Delponte involves the proximal intra-tendinous placement of a suture wire, which holds the tendon using a 5mm harpoon [73]. The guide-wire is then passed out of the proximal stump into the distal stump and out through the skin, where it is held with a crimp over a button. For those familiar with Achilles tendon surgery, it is easy to appreciate that without additional endoscopic indirect vision or ultrasound imaging, optimal intrateninous wire placement is challenging. In Soubeyrand et al.’s series of wire placement using tactile feedback, the needle was outside the tendon in 45% of cases [268]. Gianetti et al. used ultrasound to insert a variation

of Buchgraber and Passler's suture technique [98]. No sural nerve injuries occurred. Blankstein et al. have used pre-operative ultrasound to locate the rupture site and confirm end-to-end appositon of repairs following operative repair [32].

Additionally ultrasonography is a validated method to determine tendon length [25,261], the displacement of sutures within the tendon and gapping due to loading. These techniques have shown that tendon elongation correlates with functional treatment, i.e. heel rise height during rehabilitation [260].

1.4.5 Complications

Treatment outcome must also include the aim to eliminate the complications of injury as well as the complications of the management option chosen by the patient. These include thromboembolic events, sural nerve injury, soft tissue infection, calf weakness and Achilles tendon lengthening.

Deep venous thrombosis.

The mechanism of rupture has enough force to rupture the tendon also places tractional forces on the veins of the lower limb *(Figure 13)*. The injury of rupture of the Achilles tendon can result in the development of a deep venous thrombosis occurring in approximately 30% or more of patients, however, the majority of these are asymptomatic [42,78,79,167,184,217]. In a study predicting outcome following patients sustaining Achilles tendon rupture patients who did not have a DVT while immobilised post-operatively had a better combined outcome score consisting of Achilles tendon Total Rupture Score, heel-rise height test and limb symmetry heel-rise height (OR 0.31, 95% CI 0.12 to 0.80) [79].

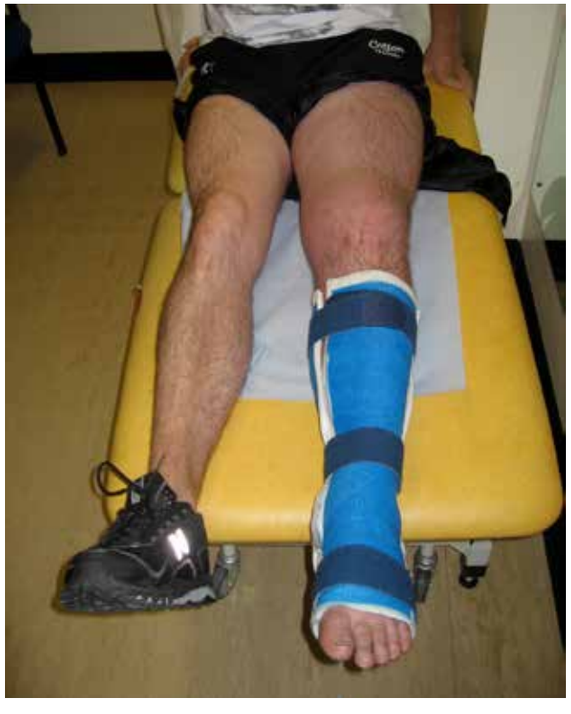


Figure 13: Deep venous thrombosis following an Achilles tendon rupture features a swollen leg with distended veins and an abnormal blue colour. Wasting of the calf muscles would be expected.

Sural nerve injury

One of the complications of Achilles tendon rupture is a sural nerve injury. This has commonly been reported related to operative repair and in particular percutaneous and minimally-invasive Achilles tendon repair [177]. Injury can occur as a result of a traction neuropraxia during the hyperflexion of the ankle at the time of injury. Eleven percent of patients suffering an Achilles tendon rupture were noted to have diminished sensation in the sural nerve distribution prior to surgery in Lim et al's. series [177]. Patients should be assessed for sensory loss on the outer aspect of the hindfoot prior to commencing treatment.

Percutaneous techniques place the sural nerve at risk, although in their original series Ma and Griffiths did not report a single case of sural nerve injury [182]. However when Hockenbury and Johns used this method, the sural nerve was entrapped by the suture in three out of five specimens [119]. Klein reported a 13% sural nerve injury rate and subsequently sucessfully modified the technique to avoid nerve injury *(Figure 14)*[157]. The visualisation, mobilisation and protection of the sural nerve is a relatively easy way to minimise iatrogenic injury [157,158,193]. Majewski compared two cohorts of differing surgical technique, one in which the nerve was exposed and protected compared with no exposure. No nerve injuries occured in the exposed group, while the iatrogenic injury rate was 18% in the non-exposed group [193]. Permanent dysaesthesia to the nerve following injury may be minimised by using absorbable sutures and temporary tenocutaneous placement [15,41,127,203,274] or rotating jigged devices externally so that guided needles miss the nerve [3,183].

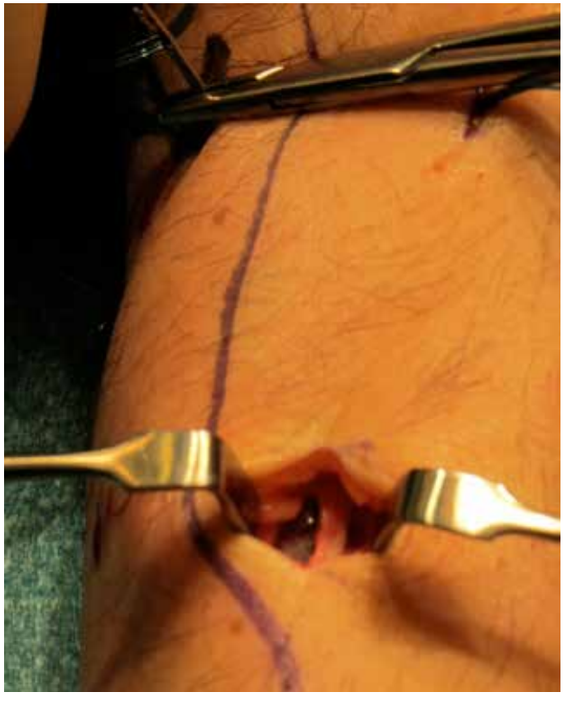


Figure 14: Exploration and protection of the sural nerve during minimally-invasive surgery reducing the rate of iatrogenic injury.

Infection

Infection is always a possibility with any type of surgery *(Figure 15)* and it must be borne in mind than choosing non-operative management does not guarantee against infection *(Figure 16)*. In Metz et al.'s's series infection is reported with non-operative management [204]. Infection due to operative treatment may be reduced by the adoption of meticulous pre-surgical skin preparation and the pre-operative administration of prophylactic antibiotics. Percutaneous and minimally-invasive suture techniques minimise the length of incisions reducing the risk of wound breakdown compared with open repair [301]. Surgeons must remember that excessive retraction may result in contused wound edges offsetting the benefits of small incisions.

Figures 15: Post-operative wound infection following operative repair.

Figure 16: Cellulitis following a cast sore occurring with non-operative management.

The use of non-absorbable sutures has been considered to increase the consequences of infection. In Marican et al's. study an infection rate of 16.7% was reported despite pre-operative antibiotics being administered. Five percent of patients required surgical debridment in addition to antibiotic treatment. Obesity, but not diabetes was found to influence the rate of infection [195].

In Cetti et al's. RCT between operative (n=56) and non-operative (n=55) management, almost equal numbers of absorbable (n=29) and non-absorbable (n=27) suture materials were used in the operative arm. Although the same Bunnell suture configuration was used in all patients, sutures of different sizes were used preventing comparison and results were not broken down into sub-groups [54]. Kocaoglu et al. reported a retrospective series comparing absorbable and non-absorbable repairs. Out of 205 patients, 7 patients had a secondary wound infection and 8 developed suture sinuses [159].

In Baig et al's. study more wound infections were noted with operative repairs performed using a No.5 non-absorbable suture (6, 31.5%) compared to a No.2 absorbable suture (0, 0%), (p=0.001), however, it must be borne in mind that the sutures were of different sizes in the different study groups [20].

When considering complications in Metz et al's. RCT, many complications were skin-related, 42% for operative treatment and 62% for non-operative treatment. The absolute risk reduction in favour of operative treatment was 15% while the relative risk reduction was 41% (risk ratio 0.59; 95% CI 0.29; 1.19) [204]. Given that patients with medical co-morbidities are more likely to select non-operative treatment, a greater number of those patients are likely to report problems with brace or cast use [125].

Calf weakness, tendon elongation and altered range of joint motion

Irrespective of the method of management of Achilles tendon rupture patients will have a reduction of calf strength of typically 10-30% [115,116,130,166,230,260,297] and may notice weakness in push-off in the sports setting. Calf weakness is present even at 10 years following rupture [24,122,164,199]. This could be considered to be a complication of the injury rather than the treatment per se.

Recent studies on the muscle pattern activation during the first year following surgery have shown that integrated electromyography was significantly higher at 6 months for the lateral gastrocnemius and at 12 months for the medial gastrocnemius than in the uninvolved side. The triceps surae muscle activations correlated moderately to the Achilles tendon length ($0.38<r<0.52$). This suggests that the loss in function of the musclotendinous complex is primarily caused by anatomical changes within the tendon [271].

The minimisation of calf weakness and recovery of strength is a key aspect of the management of patients with an Achilles tendon rupture. There is a complex interaction between calf muscle strength, ankle range of motion and Achilles tendon length leading to reduced push-off strength *(Figure 17)*.

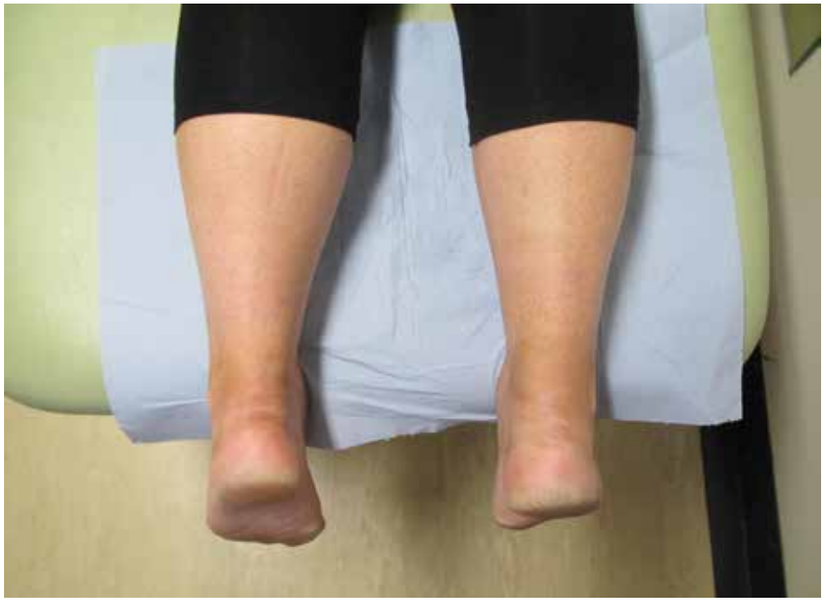


Figure 17: Following percutaneous repair this patient has calf wasting and increased ankle dorsiflexion.

Numerous studies report greater active dorsiflexion and less plantar flexion compared with the contralateral side and this may be considered to be an indirect measure of tendon lengthening. Indirect measurements of tendon length include an alteration of the arc of movement of the ankle. Ten millimeters of elongation result in a 12˚ increase in dorsiflexion [64]. With tendon elongation, the ankle will move into a position of relative dorsiflexion, however, the true arc of movement may only become apparent once full dorsi- and plantar flexion have plateaued.

In their cadaveric study using the Ma and Griffiths technique, Hockenbury and Johns, noted a 50% increase in dorsiflexion during biomechanical testing [119]. Other percutaneous repair techniques have also resulted in increased dorsiflexion. The comparison of dorsiflexion between studies is difficult as there are potential differences between active, passive and loaded movement. Tenembaum et al. evaluated percutaneous repair using the Webb-Bannister method with a No. 1 PDS suture and found 29.2˚of dorsiflexion vs. 23.4˚ on the non-injured side [276]. Dorsiflexion was increased to 7.8˚ with a loss of plantar flexion of 4.3˚ compared with the non-injured side. Partial weight-bearing was introduced at the 3 week time point and strengthening exercises commenced at 6 weeks [276]. Chan et al. compared open and minimally-invasive surgery and reported 18.5˚ of dorsiflexion +/-3.8˚ for MIS compared to 16.9˚ +/-2.9˚ for open repairs [57]. Leppilahti et al. reported increased dorsiflexion of 13 +/-5˚ for the treated side compared with 10˚ for the non-injured side. Correspondingly there was less active plantar flexion of 45˚ compared with 51˚ [174].

In Willits et al.'s study the mean dorsiflexion at 2 years was 16.4+/-6.5˚ following operative repairs and 17.2˚+/-7.8˚ in non-operatively treated patients. The dorsiflexion was measured with the patient seated supine measuring the angle between the long axis of the fibula and the lateral border of the foot, when the knee was in 30˚ of flexion. The unaffected tendons had a greater ROM than the affected tendons [297].

A range of motion comparison between affected and non-affected ankles also features as part of the Achilles rupture performance score [172]. This does, however, not relate to the location of the arc of movement. An anterior neutral point with increased dorsiflexion and reduced plantar flexion may well have the same ROM as the non-affected side.

Nistor et al. in their RCT noted small changes in ROM. The most frequent changes were increased dorsiflexion and reduced plantar flexion. In non-operative treatment a smaller loss of plantar flexion was accompanied by a gain in dorsiflexion [219].

Majewski et al. compared the outcome of 8 patients using the Thermann scale and compared ROM. A modified Bunnell No. 3 non-absorbable suture was used. Patients were either non-weight-bearing in a cast for 5 weeks or in a shoe for 9 weeks initially non-weight-bearing for 3 weeks and then weight-bearing. Increased dorsiflexion to 5˚ was noted in 11 out of 28 patients with 5 from the cast group and 6 from the shoe group [194].

During healing, Achilles tendon length has been measured during the recovery and rehabilitation process [139,211,221,222,253]. The most significant change is elongation compared with the non-injured ankle, which may account for the strength deficits [260], and in particular the weakness at the end range of plantar flexion [212] and reduced ankle joint angle at toe off 117+/- 8˚ degrees in ruptured ankles compared with 124+/-7˚ in normal ankles [226]. All management methods aim for tendon end apposition either during operative or ankle plantar flexion in functional brace or cast. The key to the prevention of elongation may be to minimise tendon end separation during early tendon loading and movement.

Operative repair enables the ends of the ruptured tendon to be directly apposed and potentially remain approximated during the early stages of the healing and rehabilitation process. Non-operative treatment aims to ensure the tendon ends are apposed. Separation of the tendon ends has been shown to result in an inferior outcome [139,140], and gapping >5mm has been considered to be biomechanical failure [171]. Nyström has reported two phases of separation following repair; an early phase in the first seven days followed by a later phase at day 22 to 35 [221]. Kangas et al. and Mortensen et al. reported elongation during the first 6 weeks following repair [139,211]. Later in the organisational phase of maturation during rehabilitation the tendon actually shortens although only by a small amount; 0.7mm [222,253]. This shortening may relate to the respiralisation of the tendon fascicles and may be associated with optimisation of gastrocsoleus strength and bulk as rehabilitation plateaus.

So far, elongation has been measured either indirectly from range of motion, directly with radio-opaque markers being placed within the tendon [54,140,211,222,253] or using radiological modalities such as either ultrasound [260,271] or computed tomography [248].

Cetti et al. compared radiographic measurements following an open repair using a Vicryl 0 suture and using a modified Bunnell configuration together with a central Tsuage suture [54]. Elongation was measured using the distance between 50 steel markers/monitoring wires placed during repair. There was a mean of 6.1mm elongation in a mobile cast compared with 13.5mm elongation in a rigid cast. The greatest change in elongation occurred between the 6 and 12 week time point with 7.5mm elongation (-3 to +16) in a mobile cast and 5.9mm (-5 to +17) elongation in a rigid cast (p=0.0345). Weight-bearing was permitted in the mobile cast but not in the rigid cast. Following cast removal weight-bearing with wedges was permitted and then calf muscle exercises during loading were commenced from the 8 week time point.

The influence of post-operative immobilisation and weight-bearing on elongation has also been studied [139,211,270]. Elongation has been found to be less in a group rehabilitated with early motion rather than cast immobilisation however statistical significance was not achieved [139,140]. Elongation correlated with clinical outcome (R=-0.42 p=0.017), with less elongation having a better clinical outcome, but more elongation with increased age, higher BMI or plantar flexion at peak torque speeds [139]. Predictive factors of increased age and a higher BMI have been noted in patient-reported outcome score and functional parameters [232]. Mortensen noted 9mm of elongation for those immobilised in cast versus 11.5mm in those managed with early motion. Separation correlated with the initial tension of surgical repair; r[S] =0.45 [211]. Schepull et al. found a median of 3.1mm elongation between weeks 3 to 7 and then 4.7mm from week 7 to week 19. After week 19; 0.7mm of shortening of the repair was noted [253].

Rosso et al. studied the influence of muscle volume and Achilles tendon length during recovery and rehabilitation following rupture [248]. Fifty-two patients were treated by open, percutaneous repair or non-operative management and received similar rehabilitation. MRI images of the musculotendinous units of both the involved and non-involved limbs were compared at the 6 months time point. Reduced muscle volume was found in all groups, however, there was a greater muscle volume in the non-operatively treated group compared with the percutaneously managed group. Muscle volume did not correlate with patient-reported outcome scores, i.e. ATRS (R^2=0.04 n.s.) and clinically measured dorsiflexion showed poor correlation with Achilles tendon length (R^2=0.07, p=0.008). The involved tendons were longer in the affected leg in all groups; involved Achilles tendon 198.4+/–24.1mm vs. non-involved tendon 180.6+/–25mm. The mean elongation was found to be 17.8mm [248]. This study suggested that Achilles tendon length cannot be restored independent of the type of treatment.

In addition to the method of repair, the post-operative management may have a role in the prevention of tendon elongation.

The duration of brace use may also be a factor affecting outcome. The majority of patients require in excess of 6 weeks of functional brace treatment following an Achilles tendon rupture, however, prolonged brace use may influence patient-reported outcome and reduce the re-rupture rate. Aujla et al. compared the outcome of patients wearing a functional brace for 8 weeks with those wearing a brace for 11 weeks in a non-operative management programme. At a minimum of 1 year follow up there was no difference in ATRS scores 76.1 points and 76 points respectively. There were no re-ruptures in the 8 week group and one rerupture

in the 11 week group [17]. The use of a brace for at risk activities for up to 4 months following injury has led to low re-rupture rates 1.1% [125]. Depending on a patient's individual require the duration of orthotic use may have a considerable impact on lifestyle and activity. This could be considered to be a complication of Achilles tendon rupture.

All patients require an explanantion of the significance of their injury for their own and their employer's understanding. The fact that the injury is usually associated with degenerate tissue with poor vascular supply implies a prolonged healing process. It may take several months before the patient is able to return to work (heavy labour) and possibly 6-9 months or longer before they are able to return to sporting activity [306].

Based upon the reported literature, the optimal operative management may be to shorten the Achilles tendon to a predictable length during operative repair. This initial tension may allow compensation for elongation during the healing and rehabilitation process and restoring eventual length of the tendon to that of the non-involved side and preventing elongation *(Figure 18)*. Further research is required to determine the optimal tightening of the Achilles tendon at the time of surgery and to determine the relationship between the resting position of the ankle, patient-reported outcome scores, heel rise and endurance during recovery and rehabilitation.

Figure 18: Following successful Achilles tendon repair and rehabilitation. This patient reported reduced initial push off after returning to recreational competitive netball.

2. Aims

Michael R Carmont

This thesis aims to evaluate and optimise the outcome of percutaneous and minimally-invasive repair following Achilles tendon rupture.

3. Objectives
Michael R Carmont

- To ensure that the Achilles Tendon Rupture Score (ATRS) is valid, reliable and responsive for an English speaking population
- To determine whether percutaneous surgical repair of the Achilles tendon is reliable, cost effective and produces comparable results to a traditional method of open surgical repair
- To evaluate the functional outcome of patients during the first year following percutaneous surgical repair of the Achilles tendon
- To determine the reliability of the measurement for the Achilles Tendon Resting Angle (ATRA)
- To determine the variation in ATRA and calf circumference with time, following rupture, repair and rehabilitation
- To compare the elongation of Achilles tendon repairs using non-absorbable sutures. To determine if the use of non-absorbable sutures would prevent increasing ATRA and lead to improved functional outcome
- To determine the biomechanical strength and intra-tendinous stability of percutaneous/minimally-invasive suture configurations of an Achilles tendon rupture model

4. Patients and Methods

Michael R Carmont

Nature of research

This thesis is based upon pragmatic research on a comprehensive cohort model to determine and optimise outcome and minimise complications following Achilles tendon rupture. Data was prospectively collected on patients who were observed longitudinally. This differentiates Practice Based Evidence form Clinical Practice Improvement [120]. Patients were recruited according to presentation, forming a longitudinal comprehensive cohort model [146].

The repair technique was modified based upon the findings of previous cohorts, and an understanding of the current literature. Additionally outcome measures and parameters were developed and evaluated to lead to an increased understanding of the outcome of patients following Achilles tendon rupture.

4.1 Patients

All patients in this thesis have been evaluated following presentation to the Shrewsbury and Telford Hospital NHS Trust with an Achilles tendon rupture. The catchment area of this District General Hospital is 300,000 to 400,000 people. Given a rupture incidence rate of approximately 10 per 100,000, the presentation of 30-40 patients p.a. is expected. All patients are counselled in terms management options consisting of an explanation of the current literature together with the outcome data from this hospital. The patients themselves decide whether to undergo operative or non-operative treatment.

4.1.1 Inclusion criteria

Following presentation in clinic and confirmation of the diagnosis of Achilles tendon rupture, the management options were discussed with all patients. This included the following information:

A rupture of the Achilles tendon is a significant injury, from which it may take up to a year to optimise function.

Whichever management route is chosen, operative or non-operative, when measured the tendon strength and push-off may be weak [54,152,166,218,219,230,253,255].

To date, scientific studies have not shown a significant difference in patient-reported and performance scores between non-operative and operative treatment [54,152,166,172,178,218,219,253,255].

Those patients who compete in sports activity, particularly sprint performance sports will have a significantly less functional weakness with operative treatment [166,230,297].

If treatment turns out well and without complication, most patients can return to their previous level of sports activity [306]. If re-rupture occurs, patients rarely return to their previous level of sports activity [205].

Patients return to work [88] earlier and have improved early function at 3 months [152] and 6 months [166] after operative treatment.

Compliance to rehabilitation regime is essential to minimise the risk of re-rupture.

The literature shows increased re-rupture rate with non-operative treatment compared with operative treatment, but there are fewer overall complications. However, if accelerated rehabilitation is used the risk of rerupture decreases [266].

The risk of a deep venous thrombosis is high following Achilles tendon rupture [113]. This is probably related to the mechanism of injury rather than surgically-related or immobilisation in a brace. This risk may be reduced by the use of low molecular-weight heparin.

Patients were included in the different studies according to their date of presentation. Studies were recruited over time between 2009 and 2015. This research comprises a comprehensive cohort model for inclusion [146]. Patients were evaluated until one year following rupture as per routine clinical evaluation.

4.1.2 Exclusion criteria

Patients were excluded from studies based upon the time elapsed following rupture and the presence of medical co-morbidities.

Acute ruptures of the Achilles tendon are those, which receive treatment within two weeks following injury [91]. Patients with injuries beyond this time point between 2-4 weeks are termed acute-on-chronic injuries and were predominantly excluded. The healing process commences immediately following rupture and unless the tendon ends are well apposed, the tendon ends can heal with separation leading to presistent dysfunction. Mobilisation of tendon ends to permit apposition can only be performed with surgical intervention once fibrous tissue starts to form. The fibrous tissue adheres the separated tendon ends to the nearby vascular paratenon. Operative release can be performed during minimally-invasive surgery, however, in this thesis these patients were excluded from the studied cohorts. [137].

Table 3: Patient demographics

Study	Dates	Cohort	Composition	Number	Median Age (Range)	Gender M:F
1	2009-2011	Patients	Heterogenous	49	48 (27-77)	36:13
2	2005-2011	Patients	Homogenous	84	43 (15-80)	70:14
3	2009-2012	Patients	Homogenous	73	43 (27-80)	60:13
4	2013	Subjects	Homogenous	16	24 (19-35)	9:7
5	2012-2013	Patients	Homogenous	26	41 (31-62)	17:11
6	2013-2015	Patients	Homogenous	70	45 (28-77)	58:12

4.2 Ethical approval

The local National Health Service Research and Ethics committee was consulted for the inclusion of all patients in this research. For patients other than those in Study VII the NHS REC deemed this to be service evaluation and formal ethical review was not required.

Study VII is a cadaveric bovine study. The animal tissue used was obtained from animals slaughtered for food consumption. Research and Development approval was granted from the Robert Jones and Agnes Hunt Hospital.

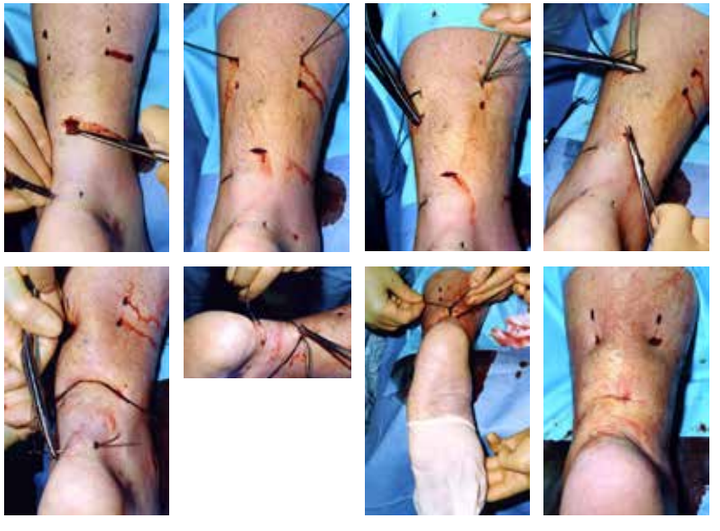
The repair technique was modified based upon the findings of previous cohorts, and an understanding of the current literature. Additionally outcome measures and parameters were developed and evaluated to lead to an increased understanding of the outcome of patients following Achilles tendon rupture.

4.3 Methods of percutaneous and minimally- invasive repair

Percutaneous Repair:

The method of tendon repair in Studies II and III was percutaneous repair *(Figure 18)*. This was performed with the patient positioned prone using a previously reported technique [46]. The majority of patients chose to have the repair performed under local anaesthesia consisting of 20mls of 0.5% Bupivucaine and 10mls 1% Lignocaine. The use of local rather than general anaesthesia is an established technique [52,53,160] and generally well tolerated. Prophylactic antibiotics 1.5g Cefuroxime or 1g Flucloxacillin were routinely administered.

The surgical incisions involved 6 stab incisions in the region of the Achilles tendon and a 1cm incision at the rupture site. The 4 proximal stab incisions are placed approximately 5 and 7 centimeters proximal to the rupture site. Clips were then used to enlarge the fascia cruris incision. A modified Bunnell suture using 4 strands of Number 1 polyglycolic acid suture (Maxon®, Covidien, Dublin, Ireland) was inserted was inserted into the proximal tendon by performing a transverse pass between proximal stab incisions and then diagonal passes to the opposing stab incision and then out of the transverse incision at the rupture site. The resistance of the tendon substance provides tactile feedback as the needle is passed. The stability of the suture is then tested by pulling firmly and the calf is inspected to check for movement in the gastrocnemius.



Figures 19: Percutaneous repair of the Achilles tendon. Ruptured tendon strands are visible from the 1cm incision over the rupture site.

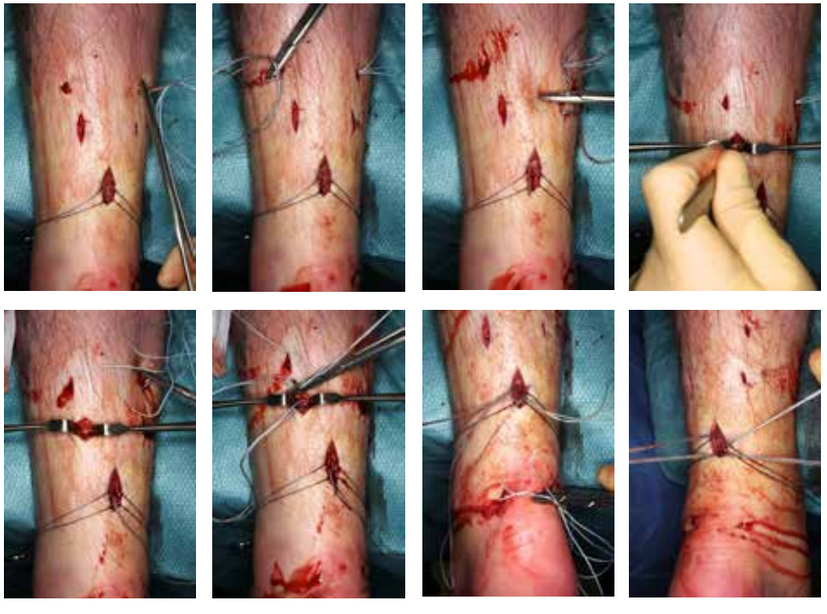
The two distal longitudinal stab incisions are placed on either side of the Achilles tendon just proximal to the insertion on the calcaneum. The anterior and posterior aspects of the distal stump are palpated using a curved clip. A modified Kessler suture is inserted by passing the needle through the tendon at the proximal end of the incision. In turn each of the sutures is then passed through the distal end of the stab incision, through the substance of the tendon and out through the incision at the rupture site. The security of the suture in the distal stump is also tested by pulling proximally.

An assistant holds the ankle in full plantar flexion to appose the tendon ends. In turn the opposing medial and lateral strands of each suture are tied, first with a surgeon's knot after which a clip is applied, and then with four further throws before the knot is pushed deep into the rupture site using a clip so that it is buried. The other strands are then tied and buried in a similar manner.

The transverse incision is closed using a subcuticular poliglecaprone suture (Monocryl®, Ethicon, Johnson and Johnson, Somerville, NJ, USA) and all wounds are then closed and covered with steristrips. Finally a preformed functional brace is applied.

Minimally-invasive repair:

Based upon a sural nerve injury rate that was considered to be unacceptable and the importance of visually confirming end-to-end apposition of the tendon repair small changes in the percutaneous operative technique were made and used in Studies V and VI *(Figure 20)*.



Figures 20: Minimally-invasive repair technique allows end-to-end apposition visualised through a 2cm incision at the rupture site. The sural nerve is also protected through the mid-lateral incision.

A 2cm midline longitudinal incision just proximal to the rupture site allowed visualisation of the tendon ends being brought into the surgical window so that an end-to-end apposition can be visually confirmed. Additionally the window allows confirmation of intra-tendinous placement of the sutures. A second 2cm longitudinal mid-lateral incision at 8-10cm from the insertion was made to visualise and protect the sural nerve. Previous studies have identified that this is the point where the sural nerve crosses the lateral aspect of the Achilles tendon [47,294]. The midline surgical incision has the advantage of being extensile and permits the fascia cruris to be closed using absorbable detensioning sutures. This has the theoretical advantage of minimising tension to the fascia cruris and optimising blood flow within the paratenon. The closure also encourages the knot to remain buried within the mass of the apposed tendon end mop heads potentially reducing the chance of patients feeling a palpable lump of knot and or suture granuloma [144,228].

This repair technique was termed minimally-invasive as the incisions used were the minimal that were required to be to ensure the key components of confirmation of end-to-end apposition, intra-tendinous suture placement, closure of the fascia cruris and protection of the sural nerve.

Table 4: Characteristics of Fiberwire and Maxon sutures.

Suture Configuration	Fiberwire®	Maxon®
Size USP	2	1
Single strand diameter/mm	0.5	0.4
Mass suture Cross Sectional Area/ mm^2	4-strand = 0.54 6-strand = 0.8	8-strand = 0.69
Material	Polytetrafluoroethylene (PTFE) coated polyester	Polyglyconate co-polymer of glycolic acid and Trimethylene Carbonate
Thread type	Braided	Mono-filament
Colour	Blue	Green
Absorption	Non-absorbable	Absorbable predictable 180 days
Ultimate tensile strength single strand	345N	54N Strength profile: 80% at 1 week 75% at 2 weeks 65% at 3 weeks 50% at 4 weeks 25% at 6 weeks

Sutures:

In Studies I, II and III, a synthetic absorbable suture was used to reduce the risk of nerve injury and entrapment, and knot prominence *(Table 4)*. Seventy-five percent of the suture's strength is maintained at 2 weeks, falling to 50% at 4 weeks and 25% at 6 weeks. The advantages of the monofilament are smooth suture passage, and the reduction of the risk of snagging the needle through the braid of a previously passed suture strand resulting in intra-tendinous knotting.

Complications were noted despite the use of the absorbable suture, but alleviated by the change from a percutaneous to a minimally-invasive technique. Therefore a natural progression was to change suture material to a non-absorbable suture.

In Study VI repairs were performed using a No. 2 non-absorbable polytetrafluoroethylene (PTFE) coated polyester suture (Fiberwire®, Arthrex, Naples, Fl, USA) *(Table 4)*. Out of concern

for the size of the knot of this braided rather than monofilament suture and since the knot would be permanent a four strand repair was performed. The advantage of the PTFE coat is that this permits smooth suture passage; however, conversely this smooth coating may reduce the strength of the knots on tying. The strength of a repair knot has been shown to be related to the number of strands across the repair site [19,234]. After patients developed increased resting posture or ATRA at the 3 month evaluation and for concern for the outcome of these patients the number of strands passing across the repair site was increased to 6. This allowed the functional evaluation of outcome of both 4-strand and 6-strand repairs.

In all patients, the same knot tying technique was used. This consisted of a mass suture knot with a double throw surgeon's knot initially and then subsequently 4 further throws. The sutures were then cut to approxiamtely 7mm from the knot and a clip was used to push the knot deep between the suture ends beneath the fascia cruris.

Post-operative functional brace:

Cast immobilisation is potentially the simplest and most traditional treatment for Achilles tendon rupture. The aspects of early movement and weight-bearing mobilisation have been long investigated [139,164,211].

Braces used include pneumatic walkers with wedges placed beneath the heel [230,291,297], controlled ankle motion devices, bespoke braces [63,84] and vacuum equinus braces [125].

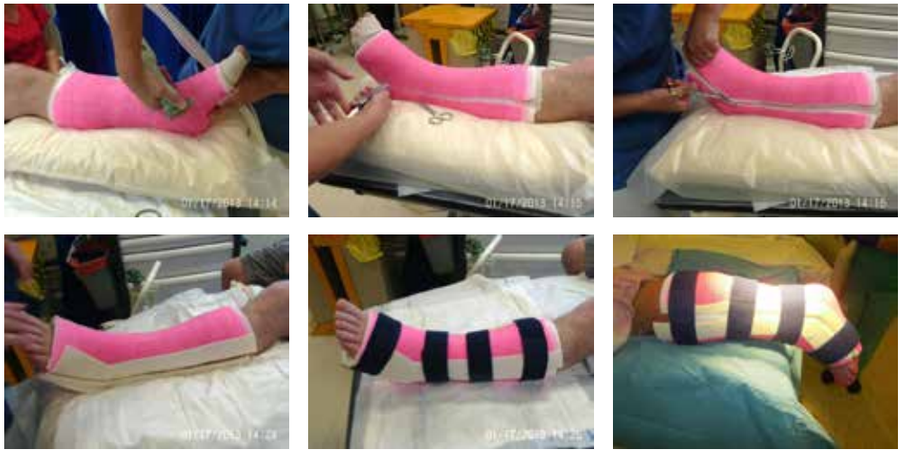
A post-operative equinus cast was used for patients treated with open repair in Study II; otherwise a functional brace was used for all patients in this thesis. The brace was prepared on the patient's first visit to hospital. The brace is prepared with the patient seated supine with the knee flexed over a knee block *(Figure 21)*. Three layers of the 15cm x 7.5cm undercast padding are applied beneath the tendon area. Two millimeters thick Hapla Fleecy Web (Cookson Gerrard and Co, Oldbury, UK) padding felt is then placed as a cutting off piece to protect the patient's skin. An additional layer of polyester stockingette is subsequently applied.

Figures 21: The preparation of the functional brace.

Strips of 7.5cm Hapla padding felt 2mm thick are applied from the metatarsal head to the level of the tibial tubercle. Undercast padding roll is then applied with a double layer around the metatarsal heads. Three layers 7.6cm of fiberglass (3M, Scotchcast Plus) are applied to the dorsal aspect of the ankle to the level of the metatarsal neck.

Two rolls of fiberglass are then applied and plantar flexion is manually encouraged until the cast material cures within 2 minutes.

After 10 minutes, the circumferential cast is then cut using an oscillating saw *(Figure 22)*. The skin is protected by the underlying Hapla felt. The halves of cast are then removed and the edges covered by strips of 2mm semi-compressed Hapla felt.



Figures 22: Further preparation of the functional brace. The patient is encouraged to weight-bare on their metatarsal heads as tolerated by discomfort following repair.

The functional brace is reapplied and elasticated velcro straps; 5x57cm are used (Ortho-Glass Strap Kit, BSN medical GMbH, Hamburg, Germany).

The brace can then be applied over undercast padding following repair. Although the preparation of this brace requires considerable technical skill, it does not take much longer than a plantar flexed synthetic cast. Patients wear the brace pre-repair and both anterior and posterior shells are applied following repair. At 2 weeks the wounds are inspected and the anterior shell re-applied with the elasticated velcro straps. Alternatively a double layer of tubigrip is applied to hold the anterior shell in situ.

The brace is light-weight, inexpensive, cost-effective and permits weight-bearing.

Following surgery a reinforced synthetic equinus cast is applied. This was made prior to surgery and then removed by splitting along the middle of the medial and lateral aspects to form an anterior/front and posterior/back shell. The sharp cut edges are covered with adhesive padding for protection.

Following surgery the anterior and posterior shells are re-applied and held in place by elasticated velcro straps. Following repair the ankle adopted a positon of increased plantar flexion compared with its position during application and curing of the cast material. To accommodate this positional change a 10cm crepe bandage was folded upon itself over a 15cm length and placed beneath the

shin to pad the anterior aspect of the anterior shell and ensure this adopts a position of comparable increased plantar flexion.

Post-operative rehabilitation:

The post-operative management was identical for all patients in this thesis except those managed with open repair in Study II. Patients who received an open repair were kept non-weight-bearing for 6 weeks in an equinus plaster cast and then referred for physiotherapy with a graduated increase in weight-bearing as tolerated.

Patients usually returned home on the day of surgery. In Studies II, III, V and VII weight-bearing was permitted, with loading on the patient's metatarsal heads as tolerated by pain, together with axillary crutches. Low molecular-weight heparin was prescribed for two weeks.

At the two week time point the wounds were inspected for infection, the calf for excessive oedema and skin sensation for sural nerve dysfunction. The posterior half of the brace was discontinued and the anterior maintained for protection whilst weight-bearing.

The principles of early accelerated rehabilitation were adopted involving protected weight-bearing in a brace and early motion [150]. An identical protocol was used for all patients managed with percutaneous repair in Study II, and all patients in Studies III, V and VII.

Immediate weight-bearing was permitted as tolerated by pain. Patients applied load through the meta-tarsal heads only with the knee flexed and using crutches and when protected using the brace. In the early stages the posterior shell protected the skin incisions and beyond two weeks the absence of the posterior shell meant that some plantar flexion was possible during weight-bearing.

Patients were encouraged to weight-bear as soon as tolerated after surgery, using crutches and a protective equinus split cast for 2 weeks and a dorsal shell for 6 weeks. Thereafter, a 15mm heel raise was provided. Active range of motion exercises, plantar flexion, inversion and eversion contractions of each 10 seconds were performed with 10 repetitions, three times per day, were commenced at two weeks.

Range of motion exercises were increased to tolerance, with knee and hip strengthening exercises and joint mobilisation. Crutch use was discontinued at 8 weeks once the gait had normalized as ROM improved towards normality to permit a heel strike. Formal physiotherapy was commenced at the 6 weeks time point consisting of gait retraining and strengthening with double heel rises progressing to single heel rises. Stretching and plyometric exercises were avoided until the 3 months time point. Running was permitted earliest at 3 months, but dependent on the individual patient's recovery. No formal restrictions were given with regards to return to sports.

4.4 Methods of outcome evaluation following Achilles tendon repair and rehabilitation

4.4.1 Timing

A baseline measurement of the ATRA was made following the application of dressings and before the application of the functional brace. Patients were then assessed in routine follow-up clinic at 2 weeks. Patients were seen at 6 weeks for ATRA and calf circumference measurements and at 3, 6, 9 and 12 months in all studies with the exception of those patients receiving open repair in Study II. Patients were evaluated for ATRA, calf circumference, and Heel-Rise Height (HRH). Heel-Rise Repetition (HRR) was assessed.

4.4.2 Patient Reported Outcome Measures

Studies II, III, V and VI

The Achilles tendon Total Rupture Score (ATRS) *(Figure 23)* was developed in 2007 to provide a self-administered validated and sensitive instrument with high reliability for symptoms and the effect of physical activity on patients following an Achilles tendon rupture [215]. Since then the ATRS has been shown to be valid, reliable and responsive outcome measure for patients with an Achilles tendon rupture in several other studies [147,148]. The score was developed on a cohort of Swedish patients and subjects for whom an inclusion criterion was to be able to read and understand the Swedish language. Initially 14 questions were generated and tested. Four of these were subsequently removed. The ATRS published in an American journal, but has not previously been adapted to English and this represented a gap in the literature. Prior to embarking on further research it was considered important to cross-culturally adapt the 2007 published version of the ATRS to make the score more understandable for the study group.

ATRS
(Achilles Tendon Total Rupture Score)

All questions refer to your limitations/difficulties related to your injured Achilles tendon.

Mark with an X in the box which matches your level of limitation!

1. Are you limited due to decreased strength in the calf/Achilles tendon/foot?

0 1 2 3 4 5 6 7 8 9 10

2. Are you limited due to fatigue in the calf/Achilles tendon/foot?

0 1 2 3 4 5 6 7 8 9 10

3. Are you limited due to stiffness in the calf/Achilles tendon/foot?

0 1 2 3 4 5 6 7 8 9 10

4. Are you limited due to pain in the calf/Achilles tendon/foot?

0 1 2 3 4 5 6 7 8 9 10

5. Are you limited during activities of daily living?

0 1 2 3 4 5 6 7 8 9 10

All questions refer to your limitations/difficulties related to your injured Achilles tendon

Mark with an X in the box which matches your level of limitation!

6. Are you limited when walking on uneven surfaces?

0 1 2 3 4 5 6 7 8 9 10

7. Are you limited when walking quickly up the stairs or up a hill?

0 1 2 3 4 5 6 7 8 9 10

8. Are you limited during activities that include running?

0 1 2 3 4 5 6 7 8 9 10

9. Are you limited during activities that include jumping?

0 1 2 3 4 5 6 7 8 9 10

10. Are you limited in performing hard physical labor?

0 1 2 3 4 5 6 7 8 9 10

Total Score:

Figure 23: The Achilles tendon Total Rupture Score [215].

After discussion, three questions were changed. In question 2, fatigue was replaced by progressive tiredness, questions 6 surfaces was replaced by ground and finally in question 10 manual labour was replaced by physical work *(Figure 24)*.

Achilles tendon Total Rupture Score (ATRS)

Hospital Number: **Date:**

Date of rupture: **Injured Side:**

Date of repair/reconstruction:

Please rate your current limitations; 10 is no limitation, 0 is severe limitation, circle your answer to the following questions.

1. Are you limited due to decreased strength in the calf/Achilles tendon/foot?
0 1 2 3 4 5 6 7 8 9 10

2. Are you limited due to progressive tiredness in the calf/Achilles tendon/foot?
0 1 2 3 4 5 6 7 8 9 10

3. Are you limited due to stiffness in the calf/Achilles tendon/foot?
0 1 2 3 4 5 6 7 8 9 10

4. Are you limited due to pain in the calf/Achilles tendon/foot?
0 1 2 3 4 5 6 7 8 9 10

5. Are you limited during activities of daily living?
0 1 2 3 4 5 6 7 8 9 10

6. Are you limited when walking on uneven ground?
0 1 2 3 4 5 6 7 8 9 10

7. Are you limited when walking quickly up stairs or up a hill?
0 1 2 3 4 5 6 7 8 9 10

8. Are you limited during activities that include running?
0 1 2 3 4 5 6 7 8 9 10

9. Are you limited during activities that include jumping?
0 1 2 3 4 5 6 7 8 9 10

10. Are you limited in performing heavy physical work?
0 1 2 3 4 5 6 7 8 9 10

Figure 24: The cross-cultural adaptation of the ATRS.

This English version of the ATRS was validated by testing on 49 patients sustaining an Achilles tendon rupture at 3, 6 and 12 months following injury.

ATRS was found to have overall excellent reliability with an ICC = 0.986, effect size of 0.93 and a minimal detectable change of 6.75 points. There was no significant difference between the results of the English and Swedish versions of the score.

The Swedish ATRS has also be validated by other British researchers, who found a high internal consistency of >0.8 Cronbach's Alpha and significant correlation ($p<0.001$) with the Disability Rating Index and EuroQol 5D [147].

Other outcome scores commonly used include the Foot and Ankle Outcome score, the American Orthopaedic Foot Ankle Society(AOFAS) Score [156], the Thermann score [280] and the Leppilahti score [172]. A systematic meta-analysis looked at 21 different outcome measures in 50 articles. Out of these only 4, the AOFAS, the Olerud and Molander Ankle Score [227], the Leppilahti score and the ATRS cited independent validation data. The ATRS has been shown to be the only outcome measure to show multiple facets of validity for patients with Achilles tendon rupture [147,148]. Additionally it was the only score with a standardised methodology for outcome measure development.

Since the original publication in 2007 and the first cross-cultural adaptation in 2009 (Study I) the ATRS score has since been adapted to Chinese [68], Dutch [233], Italian [287], Brazilian Portuguese [305], Persian [11], Turkish [145], Danish [94], and most recently Norwegian [213].

During the development of the ATRS criterion validity of the new score could not be established since no 'gold standard' score exists.

The use of prospective studies has the advantage over retrospective in that data can be collected at known time points following injury and treatment. This suggests that it is possible to compare outcomes between case series if data collection is standardised. A follow-up of a retrospectively performed series of patients does not allow comparison but only informs the reader that patients treated that way did okay. Large variations between the time elapsed following treatment may reduce the value of these findings.

This data permitted the ATRS to be compared using linear regression analysis to determine the effect of age and gender [112]. At the 3 months time point males had on average a 7 points higher score and by one year this gender difference increased to 22 points. Age, however, showed no significant effect on ATRS at either 3 months or one year. A strong association of the ATRS at 3 months and return to play after 1 year meant that the score can be used to predict patient's ability to return to sports. This also supports the construct validity of the ATRS.

Patients were asked at presentation to determine the Tegner score of their usual sport and activity level and this was also determined at each follow-up time point in addition to their Halasi score [111,275]. The Tegner score has been commonly used in lower limb sports injury surgery and after 25 years of use is considered to be an acceptable psychometric parameter of a patient administered score and to have acceptable responsiveness, with an intra-class correlation of 0.8 and minimal detectable change of 1. More specifically the Tegner score has also been used following Achilles tendon injuries [128,160].

Halasi developed a new activity score for the evaluation of ankle instability in 2004 [111]. This included 53 sports, 3 working activities and 4 general activties inserted into a 0 to 10 point category scoring system. The level of participation is divided into Top level/national team, Lower competitive level and finally Recreational level. Halasi's score correlates with the Tegner score (r=0.7565) and has been found to have high reliability.

The Physical Activity Score (PAS) was described by Gunnar Grimby to assess leisure time physical activity and divides the activity into intensity from light, moderate and hard or very hard exercise [104]. Some researchers have also added duration and frequency requirements not included in the original version. The score has predictive validity to various risk factors for health conditions [105].

Patients in Study VI were also asked if they had reached the same level of sports and physical activity or performance as before their injury. They were verbally given the options of not yet, the same or improved. This terminiology was used so that the patient could decide about their own function in respects to their sports. For example a competitive footballer may return to the same team, play in the same league and score the same number of goals but they themselves may feel they had not yet reached the same level of function. The suggestion of the answer "Not yet" was to encourage patients with strengthening exercises and remind them of the expectation to return to sport.

4.5 Objective outcome measures

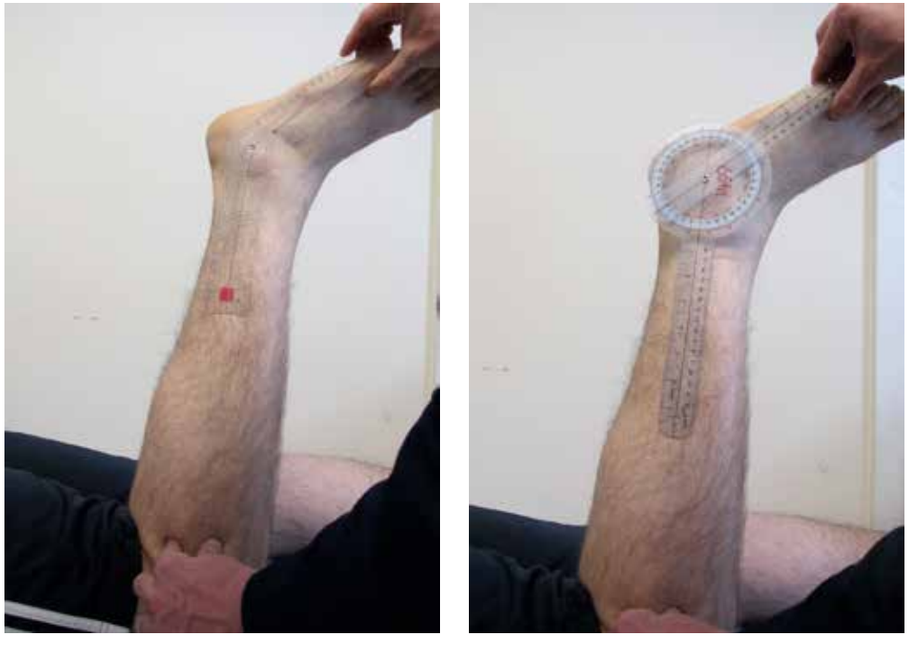
Studies III, V and VI

Patients were functionally assessed which comprised a longitudinal observation of the patients ATRA, calf circumference, Heel-Rise Height and Heel-Rise Repetition.

Achilles Tendon Resting Angle

The ATRA is defined as the angle between the long axis of the fibula and the line from the tip of the

fibula to the centre of the head of the fifth metatarsal *(Figure 25)*. Further terminology consists of an absolute angle as described above and a relative angle by comparison to the non-injured side. The non-injured side may not necessarily be normal as the tendon may have pathological change, termed tendinosis, and cause symptoms i.e. tendinopathy. Relative posture of the ankle was noted at rest following rupture, following operative repair, after removal of the functional brace and during rehabilitation. This inception was to develop a simple reproducible physical measure that could be used to compare the functional length of the gastrocnemius/soleus/Achilles complex. Through repetitive observation of this parameter, the aim was to gain greater understanding of the various processes of gaping, operative repair, separation, muscle wasting, and restoration of muscle strength tension and function. Initially it was hoped that this parameter could reflect Achilles tendon length, however, it was also appreciated that the gastrocnemius and soleus muscles will undergo a process of re-innervation following injury, gradually recover strength and bulk with rehabilitation over time.



Figures 25: The anatomical reference points of the Achilles Tendon Resting Angle used in Studies IV, V and VI.

In *Figure 26* the relative ATRA is the solid grey line compared with the dashed grey line of the non-injured side.

This increment in angle would lead to healing of the Achilles tendon with elongation and the patient would end up weak active plantar flexion and so was termed a negative ATRA.

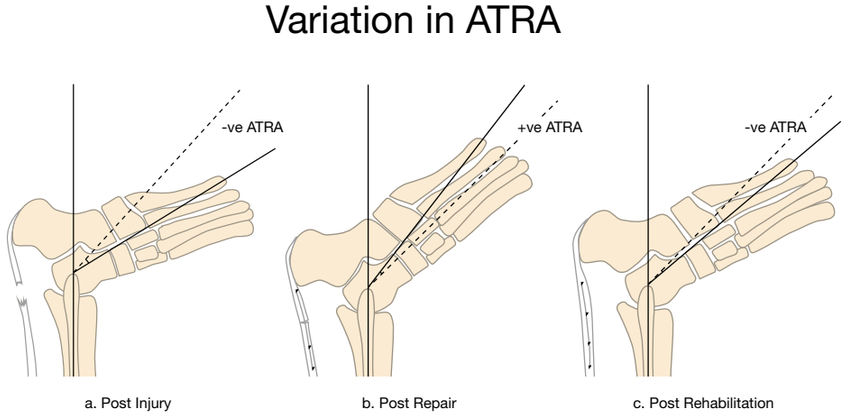


Figure 26: The hypothesised variation of the ATRA in Studies IV, V and VI. Following rupture the ATRA adopts a relatively dorsiflexed position. The solid line compared to the dashed line of the non-injured side. Following repair the ankle is relatively plantar flexed compared to the non-injured side. With brace removal and increased weight-bearing and rehabilitation the ATRA increases.

Following repair the tendon is shortened compared with the non-injured side and as a consequence the ankle is relatively plantar flexed compared with the non-injured side *(Figure 26)*. The ATRA is described/defined as positive as the Achilles tendon is relatively tight.

After brace removal, increased mobilisation and rehabilitation, the injured tendon was hypothesised to elongate and so the ATRA increases and was described/defined as negative *(Figure 26)*.

Calf Circumference

The calf circumference was measured with the patient seated with legs hanging over the edge of the examination couch ensuring they were not in contact with the the floor. A tape measure was then used to measure 15cm below the medial tibial plateau joint surface and this point was marked *(Figure 27)*.

The circumference of the calf was then measured. The calf circumference was measured on both legs and the difference determined. A reduced calf circumference indicated muscle wasting and an increased calf circumference increased the possibility of a deep venous thrombosis.

Figures 27: The calf circumference in Studies IV, V and VI was measured using a tape measure at 15cm below the medial joint line.

Heel-Rise Height (HRH)

The HRH was measured with the patient standing on a block of wood 4cm in height facing the wall. The patient was permitted to have their fingertips in contact with the wall for balance. A tape measure was then attached to the heel. The patient was then asked to perform a single heel-rise and the maximum height raised from the block was measured [259]. This was then repeated on the non-injured leg *(Figure 28)*.

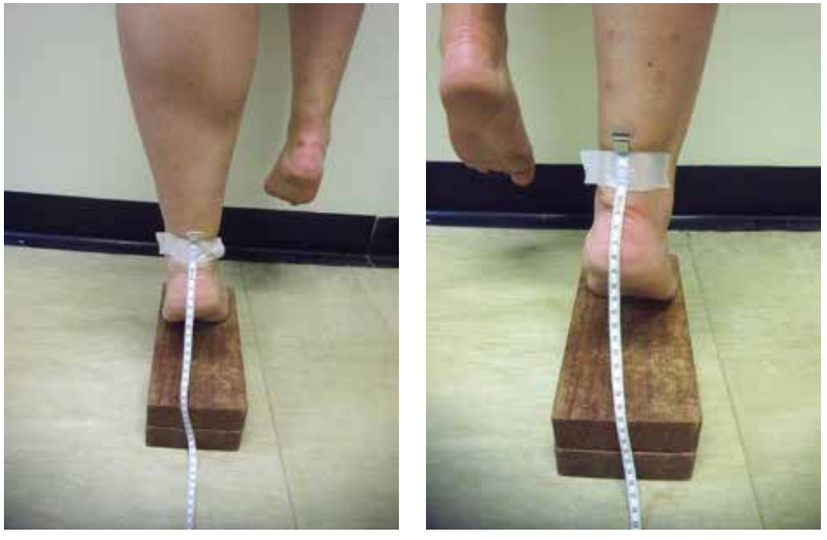


Figure 28: Heel-Rise height is determined with the patient standing on a wooden block. A tape measure is taped to the heel and the patient is asked to stand on tip toe.

Heel-Rise Repetition (HRR)

The HRR was measured with the patient standing barefoot on the floor close to the wall. The patient was asked to perform single heel rises to a maximum height until fatigue. Verbal encouragement was given to keep to a regular pace and to perform smooth maximal rises. The performance of the injured side was measured first, followed by the non-injured side.

Biomechanical methods

Study VII

Pilot testing was performed using 5 ovine tendons and 5 bovine tendons. This determined that ovine tendons were too small to insert the suture materials in the in vivo configuration and as a result bovine tendons were used. Subsequent testing of bovine tendons permitted consistent repairs to be made to allow cyclical loading to ultimate tensile failure and minimise clamp pull out. Bovine tendons have previously been successfully used to provide specimens to represent human Achilles tendons in biomechanical studies [27,74,108,234].

Specimen preparation:

Nineteen fresh frozen lower limb flexor tendons were prepared following thawing. The flexor tendon specimens were resected proximal to the musculotendinous junction and the collateral insertional slips from either side of the calcaneus.

The layers of the fascia and the paratenon were removed and the distal muscle bulk was resected off the septum. The mid-substance flexor tendon specimen sample was typically 10-12cm in length. The thinnest section of the tendon was marked with a transverse line using a surgical marking pen for the tenotomy mean (SD) thickness antero-posterior (AP) was 13.6 mm (1.6) (range 10.8-17.0mm), transverse thickness using a vernier caliper and the cross sectional area determined as 197mm^2 (30) (range 132-246) using the formula:

$$Area = \pi \bullet AP\ radius \bullet Transverse\ radius.$$

Additional transverse marks, at 3 cm and 5 cm proximally and another mark at 3 cm distally to the tenotomy line, indicated the transverse and oblique lines of suture passage *(Figure 29)*. A number 10 scalpel was then used to make a transverse tenotomy representing the rupture site. The insertion point into both sides of the calcaneus in the bovine specimens made it difficult to measure corresponding to a typical rupture site 4-6cm proximal to the insertion as in humans so the tenotomy was made at the thinnest part of the tendon.

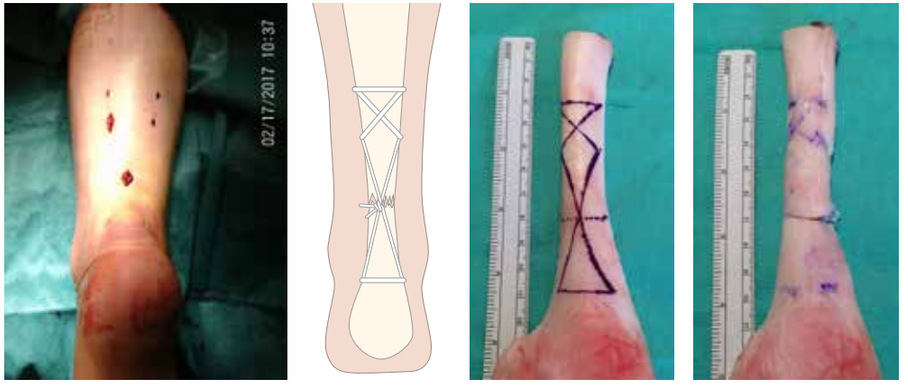


Figure 29: The repairs in the bovine tendons were similar operative technique to those performed in patients. Following dissection the bovine flexor tendons were marked using an operative marking pen to indicate a transverse tenotomy. A transverse suture pass was performed at 5cm proximal to the tenotomy and then obliquely through the tendon to 3 cm from the tentomy and a further oblique pass to the tenotomy. A distal Kessler suture was inserted at 3 cm from the tenotomy. Sutures were tied aiming for end-to-end tendon apposition.

A 9 cm B204/00 curved needle with a cutting tip was used for all suture passes (Acufirm, Ernst Kratz GmbH), threaded with 2, 3 or 4 sutures. A modified Bunnell suture was inserted through the proximal tendon 5cm from the tenotomy, at approximately a 3mm distance and was maintained between the site of the emerging needle and the position of re-insertion. Distally, a Kessler suture was formed by transversely passing the passing the needle at 3cm distal to the tenotomy *(Figure 29)*. Sutures from either end of the tendon were then tied together, using a double throw surgeons knot and 4 subsequent hitches as tight as possible with the aim of apposing the part of the tenotomised tendon ends despite the interposed suture knots.

The tendon ends were then compressed in a vice and wrapped in course sandpaper mesh before being loaded into the clamp and tightened. An initial tension of 10N was applied using a testing machine and the antero-posterior diameter and transverse diameter of the tendon measured

using a vernier caliper, in millimeters to the accuracy of two decimal places (Digitromic Caliper, Design Line Series, Moore & Wright, UK). These measurements were repeated several times until a consistent value was obtained. If apposition of the tendon ends occurred, separation was determined as zero, otherwise the initial separation was measured using the caliper. This same position on the tendon was used for all subsequent separation measurements.

Specimens were tested in random order to allow for optimisation of the surgical technique. In Group 1, 6 specimens were prepared using 4-strand Fiberwire sutures. In Group 2, 7 specimens were repaired using 6-strand Fiberwire sutures. Finally 6 specimens were repaired using 8-strand Maxon sutures. These suture numbers and combinations were chosen as they have been used in standard practice. There were no significant differences in cross sectional area between the groups (p=0.247).

Loading protocol: Tendon specimens were subject to a cyclical loading, using a hydraulic biomechanical testing machine (ESH, Brierley Hill, UK) and the output sampled using an analogue to digital converter connected to a laboratory computer *(Figure 30)*. This protocol was chosen as it has been used in testing Achilles tendon repair models to represent the early stages of rehabilitation [4,76,171]: passive ankle range of motion (100N) and walking in a controlled ankle motion walking boot with a 2.5cm heel lift (190N). The present study included 4 phases of cyclical loading:

1. *"Pre-conditioning" with 10 cycles at 100N at frequency 1Hz.*
2. *An additional sequence of 90 cycles at 100N.*
3. *A further 100 cycles at 190N.*
4. *Finally the tendon was loaded to complete failure.*

Figure 30: The tendon was clamped into a jig using sandpaper mesh and loaded using a biomechanical testing machine with computer output. A digital camera was used to record cyclical loading and testing to failure.

After each phase of loading the separation of the tendon ends was measured using the vernier caliper [234]. Clinical failure was considered to be an end-to-end separation of greater or equal to 20mm, comparable to elongation noted in non-operative management [115,116]. If a phase of loading could not be completed the number of cycles that were completed before failure was noted.

Additionally the mode of failure of each repair model was noted. Cyclical loading of the tendon was digitally recorded using a camera to determine the specific characteristics and pattern of the loading and failure of the tendon repair model.

Statistical analysis:

Data were reported as median, mean, standard deviations of ratio data and Inter Quartile Ranges for ordinal data or frequencies.

Non-parametric tests were performed on ordinal data. In Study I, test-retest analysis was performed to determine the intra-class correlation using 2-way random and Wilcoxon-paired tests. An effect size of the measure of responsiveness was calculated from the results of the 3 and 6 months evaluations. Independent samples were calculated using the Mann-Whitney U-test to compare the English and Swedish versions of the ATRS in Study I. The effect size was calculated using the mean score difference divided by the standard deviation from the initial measurement. An effect size of >0.8 was considered high.

In Studies II and III, the independent t-test was used for continuous discrete variables and ratio data, the Mann Whitney U test for ordinal data and Pearson Chi Squared test and Fishers exact test for dichotomous variables for comparison between the groups.

In Study IV, the Standard Error of Measurement (SEM) was determined for the ATRA and calculated as follows: $SEM = s^* \sqrt{(1-r)}$ where s is the standard deviation (SD) of the baseline measurements and r is the ICC. The Minimal Detectable Change (MDC) was calculated according to MDC = 2.77 x SEM. In Study IV test-retest data were analysed with intra-class correlation coefficient using ANOVA with repeated measurements. According to the recommendations of Fleiss [90], ICC values above 0.75 represent excellent reliability, values between 0.4 and 0.75 represent fair to good reliability, while values below 0.4 represent poor reliability.

The limb symmetry index (LSI) was calculated in order to compare the results from heel-rise test with the relative ATRA in Studies V and VI. The LSI was defined as the ratio between the involved limb score and the uninvolved limb score expressed as a percentage (involved/uninvolved x 100=LSI). A level of significance was set at $p<0.05$. A paired t-test was used to compare side-to-side differences. A repeated measures ANOVA, using Bonferroni correction for pair-wise analysis, was used to evaluate changes over time. Bivariate correlations were performed using Spearman's correlation.

Statistical analyses in the studies were performed using two software programmes: Matlab7.10.0 (Mathworks, Atlanta, GA), IBM SPSS Statistics Versions 19, 22 and 24 (IBM Corp, Armonk, NY).

Sample size calculations were performed for Study VI using a population mean of relative ATRA of 0˚, which compared with the sample mean of -6.5˚(6.5) at 12 months using a beta of 0.8. A sample size of 8 patients per group would be required to compare the difference in ATRA at 12 months between the 4- and 6-strand repairs. In Study VI patients who sustained complications were pragmatically included and excluded from analysis. A two-way mixed ANOVA for repeated measures using Bonferroni correction for pairwise analysis was used to evaluate changes over time between groups. In Study VI, Mauchly's test for sphericity was significant for ATRA and ATRS and significance levels were reported for Greenhouse-Geisser. Pearson's correlation was used for analyzing the correlations between the relative ATRA and HRHI and between relative ATRA and calf circumference.

The proportion of patients that had an ATRA of ≥-12˚ was also determined at each time point. Chi squared and Fischer's exact tests were performed for descriptive analysis using cross tabulations for these binomial outcome measures.

In Study VII, a sample size of six (n=6) was

used as it is the standard sample size recommended for fatigue testing (ASTM E739-91, 1998). This was consistent with group sample numbers for other Achilles tendon biomechanical studies [76,171,180,234]. Separation measurements between groups over the 4 phases of the loading protocol were compared using one-way ANOVA. Censored regression analysis was performed to evaluate ultimate failure to account for specimen pull out from the jig. For all analysis a level of significance of $p<0.05$ was chosen.

5. Summary and results of the studies

Michael R Carmont

Study I

Cross Cultural adaptation of the Achilles tendon Total Rupture Score with reliability, validity and responsiveness evaluation.

Purpose:

The Achilles tendon Total Rupture Score (ATRS) was developed because of the need for a reliable, valid and sensitive instrument to evaluate symptoms and their effects on physical activity in patient s following Achilles tendon rupture. Before using the score in future research in an English speaking population, it was decided to perform reliability, validity and responsiveness evaluations of the English version of the ATRS.

Methods:

From 2009-2010, all patients who received treatment for Achilles tendon rupture were followed up using the English version of the ATRS. Patients were asked to complete the score at 3, 6, 9 and 12 months following rupture. The ATRS was completed on arrival in the outpatient clinic (ATRS1) and again following consultation (ATRS2).

Table 5: Demographics.

	English Version (n= 49)	**Swedish Version (n=78)**
Age mean (SD)	49 (12)	42 (9)
Gender (n) Males Females	 36 13	 65 13
Type of treatment (n) Operative repair Non-operative Reconstruction	 40 4 5	 43 35 0
Time of evaluation (n) 3 months 6 months 9 months 12 months	 39 21 6 15	 0 78 0 78

Most patients (n=38) elected to have their Achilles rupture repaired using a percutaneous technique [46], one had an open repair performed at another institution, five patients had Achilles reconstruction using a peroneus brevis tendon transfer for delayed presentation [45] and one had a gracilis augmented repair due to re-rupture. Finally, four patients were managed non-operatively.

Reliability:
The English version of ATRS was shown to have an overall excellent reliability (ICC= 0.986) with no significant differences between the testing occasions *(Table 6)*. The reliability remained the same at all the different testing occasions (ICC= 0.960-0.998) *(Table 6)* with no significant differences between the testing occasions.

Table 6: Test-retest reliability – English version of ATRS.

	ATRS 1	ATRS 2	Wilcoxon paired test (p-value)	ICC
All n=81 mean (median) SD (interquartile range)	57 (55) 24.7 (40)	56 (53) 25.7 (42)	0.098	0.986
3 months n=39 mean (median) SD (interquartile range)	46 (42) 20.6 (36)	44 (43) 20.9 (34)	0.06	0.960
6 months n=21 mean (median) SD (interquartile range)	62 (65) 23.8 (46)	61 (62) 24.8 (45)	0.703	0.996
12 months n=15 mean (median) SD (inter-quartile range)	78 (90) 21.3 (34)	79 (92) 21.6 (35)	0.292	0.998

Validity:
There were no significant differences between the results between the English version and the Swedish versions when compared in a population of patients with an Achilles tendon rupture at the 6-months (p=0.088) or 12 months (p=0.179) evaluations *(Table 7)*.

Table 7: ATRS results (based on score 1 for the English version.

ATRS score	English Version	Swedish version
3 months results mean (median) SD (inter-quartile range)	n=39 46 (42) 20.6 (36)	N/A
6 months results mean (median) SD (inter-quartile range)	n=21 63 (65) 22.7 (41)	(n=78) * 72 (77) 16.8 (21)
9 months results mean (median) SD (inter-quartile range)	n=6 60 (55) 25.6 (49)	N/A
12 months results mean (median) SD (inter-quartile range)	n=15 78 (90) 21.3 (34)	(n=78) † 88 (93) 15.1 (11)

* No significant differences (p=0.088) between the British and Swedish versions at 6 months.
†No significant differences (p=0.179) between the British and Swedish versions at 12-months.

Responsiveness:
There was a significant improvement (p=0.001) in the English ATRS score from the 3 months evaluation to the 6 months evaluation (n=17). The effect size was 0.93.

The minimal detectable change:
The minimal detectable change of the ATRS score was 6.75 points.

Conclusion:
The ATRS was culturally adapted to English and shown to be a reliable, valid and responsive method of testing functional outcome following an Achilles tendon rupture.

Study II

Surgical repair of the ruptured Achilles tendon: the cost effectiveness of open versus percutaneous repair.

Purpose:
Recent meta-analyses have shown reduced re-rupture rates after surgical management of Achilles ruptures. However, percutaneous repair has been demonstrated to lead to improved function and patient satisfaction, but greater complications than open repair. In the current economic climate, it is reasonable to consider the financial cost of rupture for both the patient and the provider. The cost effectiveness of the operative treatment of ruptures of the Achilles tendon was determined based upon theatre occupancy, clinic attendance and cast changes, operative complications and the ATRS.

Methods:
The cost-effectiveness of the surgical management of Achilles tendon ruptures was audited by comparing 49 patients receiving percutaneous repair with 35 patients whom had open repairs.

Results:
There were no significant differences in terms of age, gender, side, time elapsed between injury and surgery for both groups *(Table 8)*.

Table 8: Demographics of open and percutaneous repair groups.

Variable	Open (n=35)	Percutaneous (n=49)	p-value
Gender Male/female	30/5	40/9	p=0.77
Age (years) Median (range)	41 (15-71)	45 (27-80)	p=0.09
Time elapsed from injury to repair	12 (0-42)	7 (0-22)	p=0.73
No. of patients who underwent US evaluation	4	3	p=0.45

Complications:
The complication rate was open 14.3% and percutaneous 10.4% *(Table 9)*. In addition, two patients in the percutaneous group sustained a deep venous thrombosis and another sustained an additional rupture to the injured tendon but ultrasonography examination confirmed this to be at a different site to the original rupture.

Table 9: Complications.

Complication	Open n=35	Percutaneous n=49	p-value
Infection	1 (2.8%)	1 (2.0%)	p=1.0
Wound breakdown	1 (2.8%)	0 (0%)	p=0.42
Sural nerve injury	2 (5.6%)	4 (8%)	p=1.0
Re-rupture	1 (2.8%)	1 (2.0%)	p=1.0
Prominent knot	0 (0%)	1 (2.0%)	p=1.0
Total number of complications per patient	0.14	0.18	p=0.61
Overall complication rate	14.3%	10.4%	

Functional outcome:

In the open repair group, 17 patients were lost to follow-up whereas in the percutaneous group only 3 patients were lost. Six patients were excluded from analysis due to assessment before 12 months post-surgery since they did not attend the 12 months follow-up. The one patient in the percutaneous group who sustained re-rupture at the original site received a reconstruction. At one year reasonable function was reported, although the patient also reported an exacerbation of mental health problems (ATRS = 55). This patient was not included in the functional outcome data. Although there was a significant difference in the elapsed time, functional outcome assessment was performed following surgery (Open; 48 months versus Percutaneous; 12 months (p<0.00), ATRS scores were similar (Open 89.0 (65-100) versus Percutaneous 88.8 (33-100) (0.21), *(Table 10)*.

Table 10: Patient-reported outcome (ATRS).

Variable	Open n=18	Percutaneous n=40	p-value
ATRS Mean (Range)	89.0 (65-100)	88.8 (33-100)	p=0.9
Time evaluation (months) Mean (Range)	49 (18-70)	12 (12-12)	p<0.0001

Costs:

Patients who underwent percutaneous repair spent a significantly shorter time period in hospital compared with patients who underwent an open repair *(Table 11)*. Theatre occupancy was significantly shorter with a mean tourniquet time (15mins (12-42)) for percutaneous operations compared with open procedures (43mins (26-70)) (p<0.001). Follow-up duration was longer in the percutaneous group (8.9 versus 5.0 months), however, the average number of outpatient appointments for each group was the same at 5.1. The costs of surgery have been estimated to be £935.36 for open repair and £574.04 for percutaneous repair *(Table 12)*. However, these costs exclude the financial costs of running the operating theatre.

Table 11: Estimated cost per activity based upon UK prices (conversion as of 28/10/2012).

Activity	Pounds	Euro
Day surgery bed	£72.00	€89.6
In-patient bed	£137.00	€170.5
Out-patient attendance (1:st)	£143.00	€177.9
Out-patient attendance (Subsequent)	£86.00	€107.0
Cast application Tarif	£102.48	€127.52
Cast materials Synthetic Backslab/full Plaster cast	 £12.07 £2.98	 €15.02 €3.71
Ultrasound scan	£43.00	€53.51
Open procedure total estimated cost excluding theatre time	£935.36	€1,163.89
Percutaneous procedure total estimated cost excluding theatre time	£574.05	€714.30

Table 12: Estimated costs per procedure.

Variable	Open	Estimated Open costs	Percutaneous	Estimated Percutaneous costs	p-value
Bed occupancy (days) Mean (Range) n= Cost	 2.9 (1-5) 29	 Inpatient £397.30	 1.2 (1-3) 49	 Day Surgery £72.00 In-patient £137.00	p<0.0001
Theatre time Mean mins (Range) n= Cost	 43 (26-70) 23	 Not determinable	 15 (0-42) 39	 Not determinable	p<0.0001
Clinic attendance Number of visits Mean (Range) n= Cost	 35 5.1 (2-12)	 £487	 49 5.1 (2-9)	 £487	p=0.95
Number of casts Mean (Range) n= Cost	 3.3 (0-7) 34	 £51.06	 1.6 (3.3) 49	 £15.05	p<0.0001
Total estimated costs		In-patient £935.36		Day Surgery £574.1 In-patient £639.1	

Conclusions:

This study suggests that percutaneous repair of the Achilles tendon resulted in reduced costs and yet had comparable outcome and complication rates to open repair. Percutaneous repair should be considered as the primary method of cost effective operative management of Achilles tendon rupture.

Study III

Functional outcome of percutaneous Achilles repair: improvements in Achilles tendon Total Rupture Score during the first year.

Purpose:

Randomised studies have so far failed to show a difference in outcome between operative and non-operative management of Achilles tendon rupture, provided that no rerupture occurs. Percutaneous Achilles repair has been suggested to be superior to open repair in patients with an acute Achilles tendon rupture, but there are no outcome data, using validated methods, describing the progression of recovery during the first year.

The purpose of this study was to evaluate the outcome of patients with a ruptured Achilles tendon, managed by percutaneous repair, during the first year following repair, with a valid, reliable and responsive outcome measure. Moreover, the effects of time between injury and surgery, age and complications on outcome were also evaluated.

Methods:

Seventy-three patients (60 males, 13 females) mean age of 45.5 years were included. The age, length of time between injury and surgery and complications were documented. Patients were evaluated with the Achilles tendon Total Rupture Score (ATRS) at 3, 6, 9 and 12 months following repair.

Results:

During the three years enrolment period, 76 patients chose to undergo percutaneous repair of their Achilles tendon. Of those 76 patients, two were excluded from analysis because they were lost to follow-up prior to the 3 months evaluation and accordingly there is no outcome (ATRS) data available. One patient suffered from a re-rupture at 8 weeks after injury and was not included in further analysis. The three excluded patients were all Caucasian males, with a mean (SD) age of 40 (11). Two had injured the right side and one the left side. The injury mechanism was athletic injury in two of the patients, and during ADL for one patient.

The evaluation included 73 patients. Their demographic details are typical for cohort of patients who have sustained a rupture of the Achilles tendon *(Table 13)*. There was a bimodal age distribution *(Figure 5)*. The most frequent activity during which the tendon ruptured was playing football (16), while other sports included badminton (11), running (6), rugby (5) and squash (4). All but two patients received operative repair within 14 days of injury (mean 6 days, range 0-20).

Table 13. Demographic details of Percutaneous repair group.

Variable	Percutaneous treatment
Age Mean (SD)	n=73 45.5 (11.6)
Time elapsed to repair (days) Mean (SD)	n=73 6 (3.7)
Gender Male Female	 60 13
Injured side Right Left	 35 38
Injury mechanism Sport Other external force ADL (walking)	 62 8 3
Complication Yes No	 10 63

Median ATRS scores at 3, 6, 9 and 12 months are reported in *Table 14 (Figure 31)*. The proportion of patients who reported excellent or good scores (ATRS>84) at 3, 6, 9 and 12 months were 3%, 36%, 57% and 69%.

Table 14: Patient-reported outcome (ATRS).

ATRS 3 months Median (IQR)	ATRS 6 months Median (IQR)	ATRS 9 months Median (IQR)	ATRS 12 months Median (IQR)
n=66 42.5 (31)	n=71 73 (33)	n=73 83 (27)	n=73 89 (18)

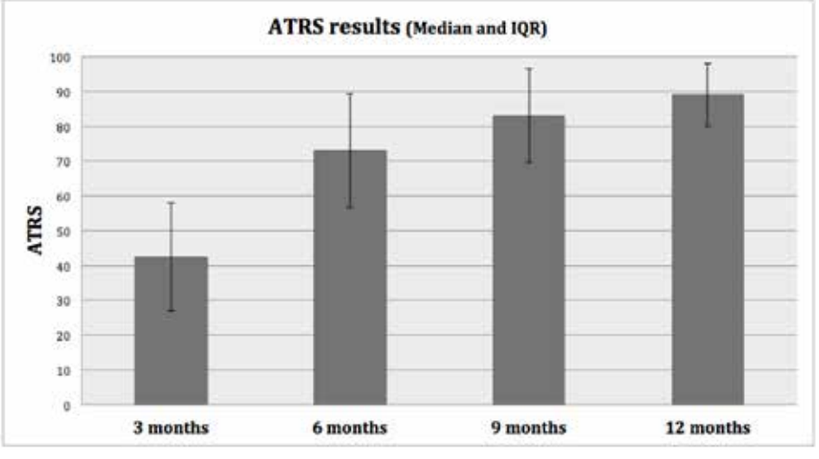


Figure 31: ATRS with time over the first year following repair.

Timing of Operative Repair:

Seven patients were treated within 48 hours and fifty patients within 7 days of injury. There are no significant differences between the groups in terms of time period concerning age, gender, injured side, mechanism of injury or outcome *(Table 15)*.

Table 15: Comparison between patients treated "early or late".

Variable	Within 48 hours n=7	After 48 hours n=66	p-value	≤7 days n=53	>7 days n=20	p-value
ATRS 3 months Median (IQR)	n=5 58 (24)	n=61 39 (33)	n.s	n=46 45 (32)	n=20 38 (23)	n.s
ATRS 6 months Median (IQR)	n=6 81 (33)	n=65 71 (34)	n.s	n=51 75 (36)	n=20 68 (30)	n.s
ATRS 9 months Median (IQR)	n=7 74 (25)	n=66 83 (28)	n.s	n=53 83 (28)	n=20 77 (34)	n.s
ATRS 12 months Median (IQR)	n=7 79 (24)	n=66 89 (14)	n.s	n=53 89 (20)	n=20 88 (14)	n.s

Age of patient:

In this study there was a bimodal age distribution. There were five patients aged 65 and older. The older age group sustained rupture during ADL rather than sport (p<0.0001). There was also a significant difference in terms of gender between the two age groups *(Table 16)*. There were no significant differences in terms of outcome at any time point.

Table 16: Comparison between the age groups.

Variable	Age 20-64 n=68	Age 65-100 n=5	p-value
Elapsed time to repair (days) Mean (SD)	6.3 (3.8)	5 (1.4)	n.s
Gender Male Female	58 10	2 3	0.037*
Injured side Right Left	32 36	3 2	n.s
Injury mechanism Sport Other external force ADL (walking)	60 7 1	2 1 2	<0.0001#
Complication Yes No	9 59	1 4	n.s
Outcome ATRS 3 months Median (IQR)	n=62 42.5 (30)	n=4 50 (45)	n.s
ATRS 6 months Median (IQR)	n=66 72 (32)	n=5 97 (50)	n.s
ATRS 9 months Median (IQR)	n=68 82.5 (26)	n=5 97 (37)	n.s
ATRS 12 months Median (IQR)	n=68 89 (15)	n=5 78 (27)	n.s

* Fischer's exact test #Pearson Chi-Square

Influence of complications:

Overall; 10 patients sustained complications. There was one case of traumatic re-rupture, four sural nerve injuries, two superficial infections, two deep venous thromboses, one prominent suture knot, and one patient suffered from adhesions. One patient experienced a traumatic re-rupture at 8 weeks following the initial repair, and was excluded from further analysis. During open reconstruction the suture material was seen to pass through the sural nerve. Thus, this patient actually suffered two complications. One patient suffered a partial re-rupture at 6 months following repair. The ATRS results of these patients are presented in *Table 17*. The overall incidence of patients suffering from complications in this series is 13.5% assuming a worst-case scenario.

There were no significant differences in the demographic details for patients who sustained complictions compared with those without complications, and notably there were no significant differences in terms of outcomes other than reduced outcome score in those sustaining a complication at 3 months (p=0.005) *(Table 18)*.

Table 17: The influence of specific complications on ATRS.

Complication	ATRS 3 months	ATRS 6 months	ATRS 9 months	ATRS 12 months
Infection	33	67	54	78.5
Sural Nerve Injury	24	DNA*	52	75
Deep Venous Thrombosis	47	99	84.5	86.5
Adhesion	17	34	77	89
Prominent knot	34	97	100	100
Partial Re-rupture	18	34	39	DNA

*DNA means that those patients did not attend for those specific outpatients appointments.

Table 18: Comparison between patients with and without complications.

Variable	Complication No n=63	Complication Yes n=10	p-value
Age (years) Mean (SD)	45.2 (11.4)	46.6 (13.2)	n.s
Time elapsed to repair (days) Mean (SD)	6.5 (3.7)	4.4 (3.1)	n.s
Gender Male Female	51 12	9 1	n.s
Injured side Right Left	32 31	3 7	n.s
Injury mechanism Sport Other external force ADL (walking)	54 7 2	8 1 1	n.s
ATRS 3 months Median (IQR)	n=57 45 (32)	n=9 31 (14)	0.005*
ATRS 6 months Median (IQR)	n=62 74 (31)	n=9 65 (68)	n.s.
ATRS 9 months Median (IQR)	n=63 84 (27)	n=10 70 (45)	n.s.
ATRS 12 months Median (IQR)	n=63 90 (13)	n=10 77.5 (28)	n.s.

* indicates a significant difference between the groups.

Conclusions:

The patients in the present study reported marked improvement in outcome between 3 and 6 months following operative repair, with continuing but less steep improvement up to one year. The presence of a complication other than re-rupture did not affect end stage outcome but did affect outcome at 3 months following repair. This study demonstrates improving scores with time over the first year following repair against which other treatment methods can be compared.

Study IV

Reliability of Achilles Tendon Resting Angle and Calf Circumference measurement techniques.

Purpose:

The resting angle of the ankle joint may be altered following apparently sucessful management of Achilles tendon rupture. The reliability of the ATRA and calf circumference measurements was determined.

Methods:

Three test-retest measurements for reliability assessment were performed on 16 healthy subjects: 10 males and 6 females.

Results:

There were 16 subjects included in this study. Nine of these were male, 7 were female. The median age was 24 years (range 21 to 35 years). The mean, range, Intra-class correlation, standard error of means and standard range for the ATRA and calf circumferences are shown *(Table 19)*.

Table 19: The mean, range, Intra-class correlation, standard error of means and standard range for the ATRA and calf circumferences.

Measurement	1	2	3	Mean	Intra-class correlation	SEM
Left ATRA Mean Range	49.4˚ (26-64)	50.1˚ (24-60)	50.5˚ (28-60)	50.1˚ (26-61.3)	0.92 (CI [0.83-0.97])	2.4˚
Right ATRA	49.3˚ (26-60)	50.5˚ (24-62)	50.0˚ (28-60)	49.9˚ (26-60.7)	0.91 (CI [0.80-0.96])	2.6˚
Left CC	38.3 cm (33.4-44.6)	38.8cm (33-45.1)	38.5cm (33-44)	38.5cm (33.2-44.2)	0.97 (CI [0.92-0.98])	0.6cm
Right CC	38.4cm (33.5-42.7)	38.6cm (33.3-44.2)	38.4cm (33.2-44)	38.4cm (33.3-43.6)	0.97 (CI [0.94-0.99])	0.5cm

ATRA means Achilles Tendon Resting Angle, CC means calf circumference and SEM means Standard Error of Means.

The standard error of the means were found to be 2.6˚ and 2.4˚ for right and left angles, respectively and 0.52 cm and 0.57 cm for right and left calf circumference measurements. All 4 of the measurements had excellent reliability, with the circumference measurement having slightly higher reliability.

Conclusions:

The ATRA and calf circumference at 15cm from the antero-medial joint line had excellent test-retest reliability. These are simple, quick and inexpensive measurements, which have the potential to correlate with tendon elongation and functional outcome. The ATRA may be used as a guide to tendon length during intra-operative repair and rehabilitation.

Study V

The Achilles Tendon Resting Angle as an indirect measure of Achilles tendon length following rupture, repair and rehabilitation.

Purpose:

Rupture of the Achilles tendon may result in reduced functional activity and reduced plantar flexion strength. These changes may arise from elongation of the Achilles tendon. An observational study was performed to quantify the ATRA in patients following Achilles tendon rupture, operative repair and rehabilitation respectively.

Method:

Between May 2012 and January 2013, 26 consecutive patients (17 male), with mean (SD) age of 42 (8) were included and evaluated following injury, minimally-invasive repair using an 8 strand absorbable suture. and rehabilitation at 6 weeks, 3, 6, 9 and 12 months. Outcome was measured using the ATRA *(Figure 32)*, Achilles tendon Total Rupture Score (ATRS) and Heel-Rise Height test.

Results:

Of the cohort of 26 patients, 3 were lost to follow-up at 12 months (n=23). On clinical assessment following injury, the mean (SD) absolute ATRA was 55˚ (8) on the injured side compared with 43˚ (7) ($p<0.001$) for the non-injured side. Immediately following repair the ATRA was 37˚(9) ($p<0.001$). This had not increased by the 6 week time point, 40˚ (7), (n.s.), however, the ATRA had increased at the 3 month time point to 52˚ (8), (P=<0.001) *(Figures 33 & 34)*. The relative ATRA was -12.5˚ (4.3) following injury and was reduced to 7˚ (7.9) following surgery ($p<0.001$). At the 6 week and 3 months time points the relative ATRA had significantly decreased to 2.6˚ (6.2) (P=0.04) and -6.5˚ (6.5) respectively, ($P<0.001$). After the 3 months time point, the ATRA did not change significantly *(Figure 34)*.

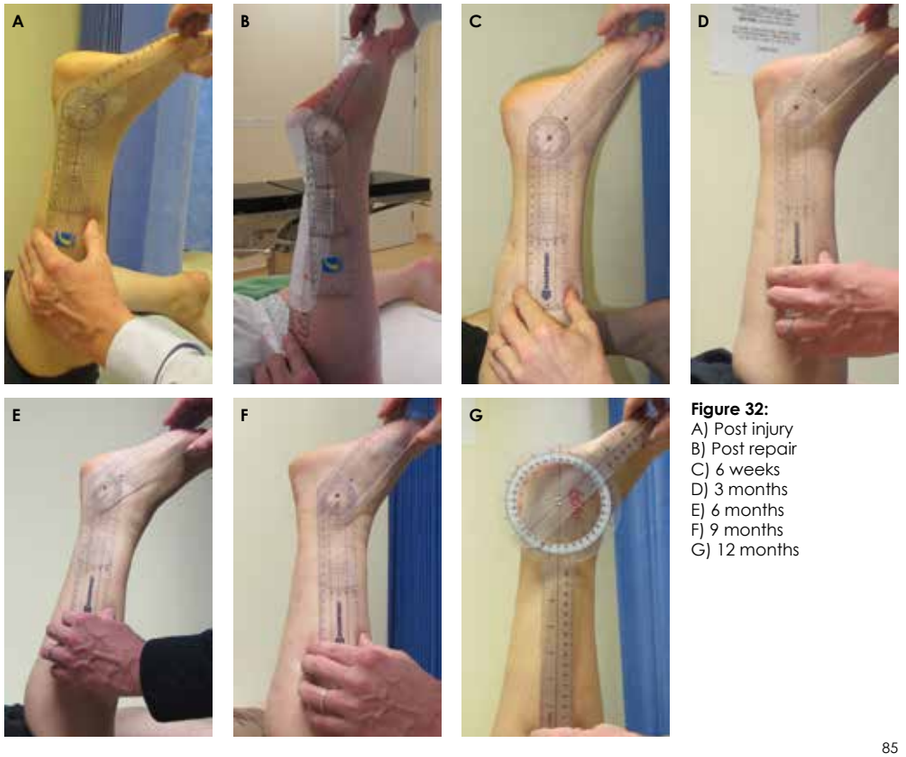


Figure 32:
A) Post injury
B) Post repair
C) 6 weeks
D) 3 months
E) 6 months
F) 9 months
G) 12 months

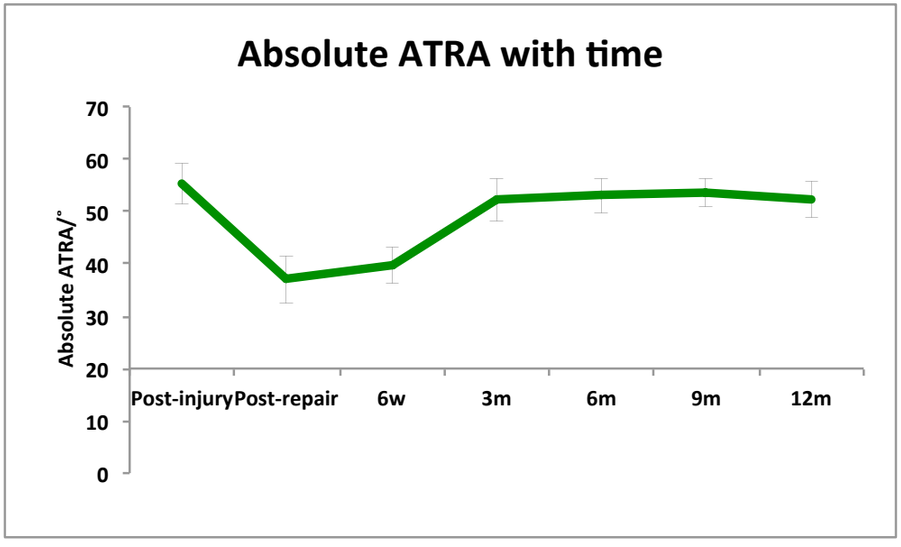


Figure 33: The behaviour of the mean absolute ATRA over time.

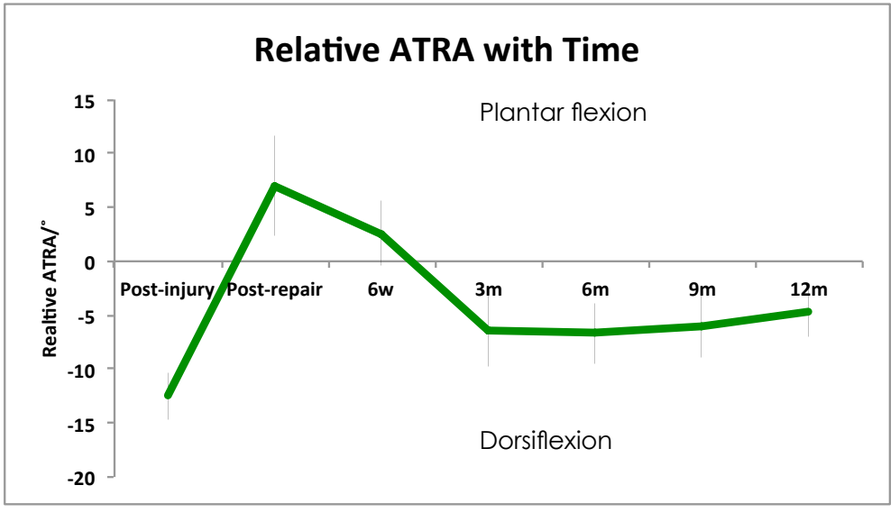


Figure 34: The behaviour of the mean relative ATRA over time.

For the 10 patients who chose general anesthesia, the ATRA was compared when the patients were awake and measured in the clinic and whilst under general anaesthesia. The absolute and relative ATRA was 50.6˚(4.6) and -11.3˚(1.7) when awake and 52.2˚(4.4) and -14˚(3.7) when measured under general anesthesia (n.s.).

There was a significant ($p<0.001$) improvement in symptoms, as measured with ATRS, over time *(Table 20)*. However, there was no significant improvement between 9 and 12 months following surgery, ATRS 85(10) and 88(13) respectively. At 3 and 6 months, the absolute ATRA showed a significantly positive association with ATRS ($r= 0.63$, $p=0.001$, $n=26$), and ($r=0.46$, $p=0.027$, $n=23$) respectively.

Table 20: The relationship of ATRS with time and Tegner score.

	Pre-injury	3 months	6 months	9 months	12 months
ATRS Mean (SD) Median (range)		45 (20) 40 (13-82)	70 (16)* 72 (39-97)	85 (10)* 86 (10-100)	88 (13) 91 (54-100)
Tegner Median (range)	7(1-9)	3.5 (0-5)	5 (1-7)	5 (1-7)	6 (1-8)
Correlation between ATRS and Tegner r (p-value)		0.291, (n.s.)	0.435, (0.049)†	0.511, (0.013)†	0.52, (0.011)†

* indicates significant (<0.01) difference compared to previous measurement.
† indicates significant (<0.01) difference compared to previous measurement.

The mean Heel-Rise Height LSI was 66%(22) at 9 months and 82%(14) at 12 months. At 12 months the absolute ATRA correlated with heel-rise height LSI ($r=-0.63$, $p=0.002$, $n=22$) but not at 9 months.

The maximal mean reduction in calf circumference occurred at the 6 weeks time point; -1.9cm (1.5). This hypotrophy decreased over time, but had not recovered by 12 months following repair; -1.1cm (1.5).

At the 9 months time point, only 14% of patients had returned to the same or an improved level of sports activity compared with pre-operative; at 12 months, 59% had returned to the same or improved perceived level of sports and 61% to their pre injury Tegner score. The ATRS correlated with the Tegner score at 6, 9 and 12 months post-injury *(Table 20)*.

One patient sustained a re-rupture (slipped on a wet floor) at the 8 weeks time point, and two others missed the final assessment. One patient sustained a superficial infection, chronic regional pain problems and a deep venous thrombosis (DVT). Altogether, two patients (8%) sustained DVT, despite thromboprophylaxis, and their calf circumference data were excluded from further analysis. One patient sustained an iatrogenic nerve injury related to the incision at the rupture site. The symptoms had resolved at 3 months. There were no other complications.

Conclusions:

The ATRA increases following injury, is reduced by surgery, and then increases again during initial rehabilitation. The angle also correlates to patient-reported outcomes early in the rehabilitation phase and with heel-rise height after one year. The ATRA can therefore be considered as a simple and effective means to evaluate function one year after following Achilles tendon rupture.

Study VI

The functional outcome of Achilles tendon minimally-invasive repair using 4 and 6 strand non-absorbable suture: a cohort comparison study.

Purpose:

The aim of management of Achilles tendon rupture is to reduce tendon lengthening and maximise function, whilst reducing the re-rupture rate and minimising other complications. A prospective cohort study was performed to determine changes in ATRA, Heel-Rise Height, patient reported outcome, return to play and the occurrence of complications following minimally-invasive repair of Achilles tendon ruptures using non-absorbable sutures.

Methods:

Between March 2013 and August 2015, 70 patients (58 male), mean (SD) age of 42 (8) years, were included and evaluated following injury and repair at 6 weeks, 3, 6, 9 and 12 months. Minimally-invasive repair was performed using either 4-strand or 6-strand non-absorbable sutures. Following surgery, patients were mobilised, fully weight-bearing using a functional brace. Early active movement was permitted from two weeks.

Results:

Seventy patients with a mid-portion rupture of the Achilles tendon were evaluated following injury and received operative repair *(Table 21)*. The activities during which ruptures were sustained included: Football (20%, n=13), Badminton (10.8%, n=7), children's sports (9.2%, n=6), Stepping in a hole, or a fall on an uneven surface (7.7%, n=5), Cricket (6.2%, n= 4), Netball (6.2%, n=4), Squash (6.2%, n=4), pushing vehicle (6.2%, n=4), slipping on the stairs (6.2%, n=4), other activities n=8, notably 4 patients were injured participating in cross fit (3.1%, n=2) and rural activities (3.1%, n=2).

Two patients sustained re-ruptures; both had been repaired using 6-strand repairs. One slipped on a wet surface and another stumbled whilst intoxicated at 4 and 5 weeks following repair respectively. Neither patient was wearing a protective brace as advised. Additional operative complications were; cellulitis, suture sinus, second site rupture managed non-operatively, failed surgery with inability to appose tendon ends (all 1.5%, n=1), *(Table 21)*. Sixty-five patients formed two comparative groups *(Table 22)*. Other than the number of patients, there were no significant differences in the demographic characteristics between the two groups.

Table 21: Patients evaluated for include and excluded from the study.

Evaluated	Acute mid-substance ruptures of the Achilles tendon having operative repair within 14 days of injury (n=70)
Exclusion	Acute-on-chronic and chronic ruptures, defined as greater than 14 and 28 days following injury respectively. Re-ruptures (2.9%, n=2) Failed surgery (1.5%, n=1) Prolapsed inter-vertebral disc causing calf weakness (1.5%, n=1) Unavailability for follow-up (1.5%, n=1)
Relative exclusion	Patients with DVTs (9%, n=6) were excluded from calf circumference analysis One patient was excluded from calf circumference, heel rise height and endurance analysis at 12 months due to pregnancy (1.5%, n=1) Previous contra-lateral rupture (1.5%, n=1)

Table 22: Patient demographics.

	Overall	Group 1 (4-strand)	Group 2 (6-strand)
Number of patients	65	19	46
Age (years) Median (Range)	45 (28-77)	44 (29-64)	46 (28-77)
Side Left:Right	31:34	10:9	21:25
Gender Male:Female	53:12	15:4	38:8
Tegner Pre-Injury Median (Range)	7 (2-9)	7 (3-8)	7 (2-9)
Time elapsed from injury to repair/ (days)	6 (1-14)	4 (2-13)	6 (1-14)

There were no significant differences in demographic characteristics between the two groups.

The changes in the relative ATRA are shown in *Table 23* and *Figure 35*. There was no difference in ATRA between the groups (n.s.). The relative ATRA increased significantly until the 3 months time point, after which the angle increased significantly to 12 months (p=0.005).

Table 23: Comparison of the relative ATRA with time between Groups: Group 1 (4-strand repair) and Group 2 (6-strand repair). There was no significant difference between the groups.

Relative ATRA/ Degrees	Post Injury	Post Repair	6 weeks	3 months	6 months	9 months	12 months
Group 1 Mean (SD)	-12.5 (6.7)	6.6 (4.3)	-0.1 (7.0)	-9.1(6.0)	-8.3 (5.1)	-7 (5.9)	-6.2 (4.0)
Group 2 Mean (SD)	-13.3 (6.8)	8.0 (5.0)	0.8 (7.7)	-6.2 (4.9)	-6.0 (4.3)	-5.1 (4.4)	-4.8 (3.9)
Overall Mean (SD)	-13.1 (6.7)	7.6 (4.8)	0.6 (7.4)	-7.0 (5.3)	-6.6 (4.6)	-5.6 (4.8)	-5.2 (3.9)

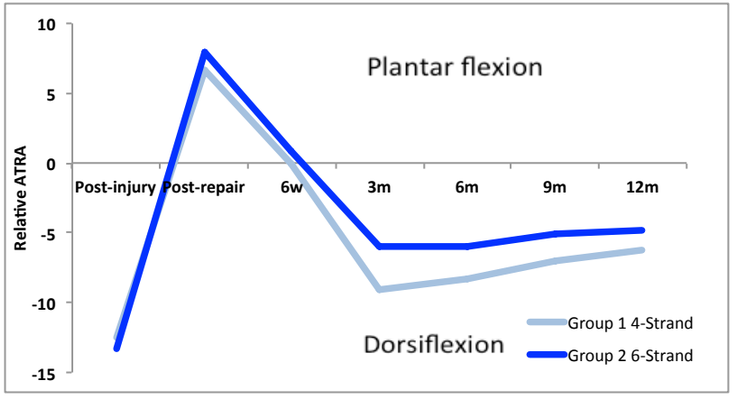


Figure 35: The changes of the ATRA Angle with time post injury, operative repair and at 6 weeks, 3 months, 6 months, 9 months and 12 months following repair. A positive ATRA is relative ankle plantar flexion compared with the non-injured side.

The proportion of patients receiving a 4-strand repair who had an ATRA ≥-12˚ was almost twice that of having a 6-strand at the 3 months time point, however, this had fallen to 1.5 times by the 12 months' time point, but with no significant difference between groups *(Table 24)*.

Table 24: Percentage and number of patients in Group 1 (4-strand repair) and Group 2 (6-strand repair) with an ATRA ≥-12˚.

	6 weeks	3 months	6 months	9 months	12 months
Overall	6.2 (4/65)	20.3 (13/64)	10.8 (7/65)	13.8 (9/65)	8.3 (5/60)
Group 1 (4-strand)	5.2 (1/19)	31.6 (6/19)	21.1 (4/19)	21.1 (4/19)	10.5 (2/19)
Group 2 (6-strand)	6.5 (3/46)	15.6 (7/45)	13 (3/46)	10.9 (5/46)	7.3 (3/41)
p-value between groups	n.s.	n.s.	n.s.	n.s.	n.s.

There were significant improvements in symptoms over time, as measured with ATRS until 12 months *(Figure 36, Table 25)* with no differences between the two groups (n.s.). The ATRS was significant for all pair-wise comparisons.

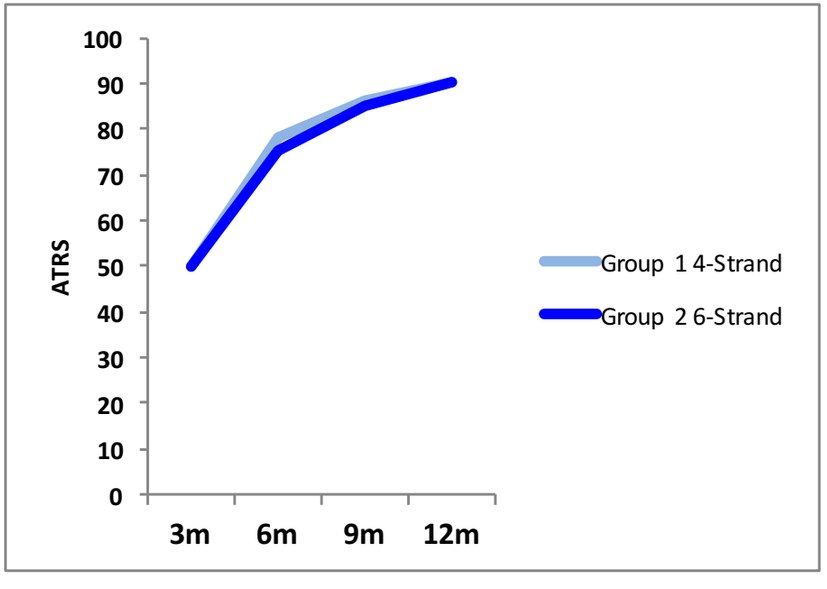


Figure 36: Comparison of the ATRS over time between Group 1 (4-strand repair) and Group 2 (6-strand repair). There were no significant differences between the groups (n.s.).

Table 25: Comparison of the ATRS over time between Group 1 (4-strand repair) and Group 2 (6-strand repair) and overall. There were no significant differences between the groups (p=0.827).

ATRS	3 months	6 months	9 months	12 months
Group 1 Median (Range) Mean (SD)	 55 (14-80) 50(22)	 76 (57-98) 78 (14)	 92 (48-100) 86 (14)	 93 (45-100) 90 (14)
Group 2 Median (Range) Mean (SD)	 45 (3-86) 50 (17)	 77 (28-98) 75 (16)	 89 (52-100) 86 (13)	 94 (35-100) 90 (13)
Overall Median (Range) Mean (SD)	 45 (3-86) 50 (18)	 77 (28-98) 76 (15.2)	 89 (48-100) 86 (13.2)	 93 (35-100) 90 (13)
p-value		<0.0001	<0.0001	0.005

The maximal mean (SD) reduction in calf circumference occurred at the 6 weeks time point; -2.0 (1.6) cm. This hypotrophy improved with time, but circumference was still reduced at 12 months following repair; -1.3 (1.0) cm. There was significant calf hypotrophy from rupture until 6 weeks and then from 6 weeks to 3 months (p<0.001) *(Table 26)*. The calf increased in circumference from 3 to 6 months (p=0.012) and then after this time although the calf increased in size; however, the improvement was not significant. Calf circumference at 6 and 9 months only weakly correlated with the relative ATRA at 12 months (r=0.316, p=0.019 and r=0.285, p=0.035).

Table 26: Comparison of the changes in calf circumference difference between the two groups. There were no significant differences between the two groups.

Calf Circumference Difference/cm	Post Injury	6 weeks	3 months	6 months	9 months	12 months
Group 1 Mean (SD)	0.18 (1.4)	-2.2 (1.2)	-0.7 (1.3)	-0.8 (1.6)	-1.1 (1.1)	-1.3 (1.0)
Group 2 Mean (SD)	-0.1 (1.2)	-1.9 (1.8)	-0.9 (1.4)	-1.3 (1.3)	-1.6 (1.1)	-1.3 (1.0)
Overall Mean (SD)	0.0 (1.3)	-2.0 (1.6)	-0.9 (1.3)	-1.2 (1.4)	-1.4 (1.1)	-1.3 (1.0)

At the 12 months time point the mean Heel-Rise Height Index (HRHI) and Heel-Rise Repetition Index (HRRI) were mean (SD), 81%(0.22) and 82.6%(0.17). The HRHI improved significantly over time, between 6 and 9 months (p<0.001) and 9 and 12 months (p=0.047). The mean (SD) HRHI at 6 months was 66% (26%) in Group 1 69.5%(27.0%), Group 2 65%(26.3%). At 9 months the mean HRHI was 75.3% (21.4%), with 81.6%(18.9%) in Group 1 and 72.7%(22.0%) in Group 2. Overall HRHI improved to 81.7% (22%) at 12 months, 83.5%(16.6%) for Group 1 and 80.9%(23.8%) for Group 2 *(Figure 37, Table 27)*. There were no significant differences in HRHI over time between the groups (p=0.323). In both Groups 1 and 2, ATRA correlated with HRHI; however, ATRA was not found to correlate with HRRI in Group 2.

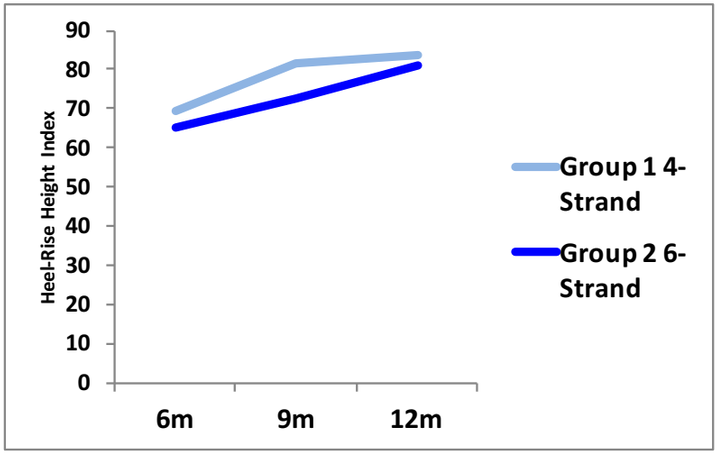


Figure 37: Comparison of the Heel-Rise Height Index (HRHI) over time between Group 1 (4-strand repair) and Group 2 (6-strand repair).

The overall relative ATRA at 3 months and 12 months both moderately correlated significantly with HRHI at 12 months (r=0.617; p<0.001, and r=0.535; p<0.001) respectively. For both Groups 1 and 2 there were significant correlations between ATRA at 3 months and ATRS and HRHI at 12 months *(Table 27)*.

The ATRA was not found to correlate with HRRI in Group 2. The relative ATRA had no significant correlation with HRRI at 3, 6, 9, and 12 months (r=0.209; p=0.276, r=0.303; p=0.104, r=0.214, p=0.264 and r=0.327; p=0.083). At 12 months the HRRI correlated with the HRHI (r=0.449; p=0.013).

Table 27: Correlation between ATRA and ATRS and HRHI.

ATRA at time point and Group	HRHI 9 months (p-value)	ATRS 12 months (p-value)	HRHI 12 months (p-value)	HRRI 12 months (p-value)
3 months Group 1	0.59 (0.013)*	0.624 (0.006)*	0.698 (0.002)*	
3 months Group 2	0.017 (0.913)	0.421 (0.006)*	0.666(<0.0001)*	0.209 (0.276)
6 months Group 1	0.589 (0.016)*	0.344 (0.176)	0.721 (0.001)*	
6 months Group 2	0.002 (0.987)	0.307 (0.048)*	0.398 (0.01)*	0.303 (0.104)
9 months Group 1	0.761 (<0.0001)*	0.486 (0.048)*	0.717 (0.002)*	
9 months Group 2	0.489 (0.001)*	-0.068 (0.675)	-0.006 (0.973)	0.214 (0.264)
12 months Group 1	0.845 (<0.0001)*	0.588 (0.01)*	0.800 (<0.0001)*	
12 months Group 2	0.005 (0.974)	0.367 (0.018)*	0.488 (0.001)*	0.327 (0.083)

* indicates significant correlation.

Patient's Perception of their Performance (PPP) in terms of return to sports was noted *(Table 28)*. There were no significant differences of PPP between the two groups: 4-strand and 6-strand repairs (p=0.685).

Table 28: Patient's perception of performance of RTP over time and between Groups.

Return To Play	6 months %(n)	9 months %(n)	12 months %(n)
Not yet:			
Group 1	84 (16)	67 (12)	47 (7)
Group 2	89 (40)	58 (26)	46 (27)
Overall	88 (56)	64 (38)	45 (20)
Same pre-injury:			
Group 1	16 (3)	28 (5)	40 (6)
Group 2	11 (5)	40 (18)	45 (26)
Overall	13 (8)	37 (23)	45 (20)
Improved			
Group 1	0	6 (1)	13 (2)
Group 2	0	2 (1)	10 (6)
Overall	0	3 (2)	9 (4)
Same and Improved			
Group 1	16 (3)	33 (6)	53 (8)
Group 2	11 (5)	42 (19)	55 (32)
Overall	13 (8)	40 (25)	54 (24)
Tegner			
Group 1	5 (3-5)	5 (5-7)	6 (3-8)
Group 2	5 (1-8)	5 (1-8)	5 (3-9)
Overall	5 (1-8)	5 (1-8)	5 (3-9)

At the 3 months' time point 19/61 (31.1%) of patients were able to perform a single heel rise (SHR) whereas the 59/63(93.7%) were able to do so at the 6 months time point. Four patients were unable to perform a SHR at 6 months. One patient was from Group 1 and 3 patients from Group 2. The patients in Group 2 continued to be unable to perform a SHR by 12 months.

Conclusions:

Increasing the number of suture strands from 4 to 6 does not alter the ATRA or Heel-Rise Height Index following minimally-invasive Achilles tendon repair. The use of a non-absorbable suture during minimally-invasive repair when used together with accelerated rehabilitation did not prevent the development of an increased relative ATRA. The ATRA at 3 months following operative repair correlated with heel-rise height at 12 months.

Study VII

Tendon end separation with loading in an Achilles tendon repair model: comparison of non-absorbable vs. absorbable sutures.

Purpose:

Rupture of the Achilles tendon often leads to long-term morbidity, particularly calf weakness associated with tendon elongation. Operative repair of Achilles tendon ruptures leads to reduced tendon elongation. Tendon lengthening is a key problem in the restoration of function following Achilles tendon rupture. This study was performed to determine differences in initial separation, strength and failure characteristics of differing sutures and numbers of core strands in a percutaneous Achilles tendon repair model in response to initial loading.

Methods:

Nineteen bovine Achilles tendons were repaired using a percutaneous/minimally-invasive technique with a combination of a modified Bunnell suture proximally and a Kessler suture distally, using non-absorbable 4-strand and 6-strand repairs and absorbable 8-strand sutures. Specimens were then cyclically loaded using phases of 10 cycles of 100N, 100 cycles of 100N, 100 cycles of 190N consistent with early range of motion training and weight-bearing, before being loaded to failure.

Results:

In 15 (79%) specimens the suture configuration

permitted end-to-end tendon apposition when positioned on the testing jig and subjected to an initial load of 10N *(Table 29)*. Two specimens in each of the 4-strand and 8-strand groups had initial separation rather than apposition due to the interposed knots between the tendon ends. Only one specimen in the 6-strand group did not have an initial end-to-end apposition.

Table 29: The separations of the Achilles tendon repair models with the 4 phases of loading, and the mode of failure.

Specimen number	Strand	Cross-sectional area/mm2	Initial Separation (10N)/ mm	Separation (10 cycles 100N)/mm	Separation (100 cycles 100N)/mm	Separation (100 cycles 190N)/mm	Ultimate Tensile Failure/N	Mode of Failure
1	4	143.3	2.9	6.8	10.3	20.5	241	Pull out jig
2	4	170.5	0	6.7	9.3	17.0	405	Distal pull out
3	4	192.8	0	3.1	5.3	15.4	399	Knot Failure
4	4	222.3	0	7.1	10.2	19.6	411	Pull out jig
5	4	166.3	3.0	6.0	8.6	16.6	464	Suture snap
6	4	188.3	0	5.6	7.4	15.3	508	Distal pull out
Mean(SD)			1.0 (1.5)	5.9 (1.5)	8.5 (1.9)	17.4 (2.2)	465 (27)	
1	6	221.4	3.9	7.7	13.7	23.5	321	Pull out jig
2	6	131.9	0	2.6	5.4	12.8	419	Proximal pull out
3	6	245.9	0	2.5	3.4	9.4	462	Pull out jig
4	6	173.8	0	5.4	8.7	17.7	567	Distal pull out
5	6	193.8	0	3.7	5.1	13.5	464	Knot Failure
6	6	214.5	0	2.6	14.5	16.3	638	Pull out jig
7	6	207.2	0	3.6	6.9	17.3	506	Pull out jig
Mean(SD)			0.6 (1.5)	4.0 (1.9)	8.2 (4.3)	15.8 (4.5)	543 (50)	
1	8	207.8	1.8	10.8	13.8	27.1	286	Pull out jig
2	8	212.6	0	8.5	10.7	21.6	506	Distal pull out
3	8	176.3	0	12.6	20.2	Failed		Knot failure
4	8	229.8	0	12.4	17.7	Failed		Knot failure
5	8	201.1	2.4	14.8	19.1	31.7	591	Distal pull out
6	8	233.6	0	10.0	13.3	26.2	526	Pull out jig
Mean(SD)			1.1 (1.4)	11.0 (2.7)	14.2 (3.5)	26.6 (4.1)	422 (81)	

The Crossectional area of the ellipsoid tendons were determined using the formula: Area=π•AP radius•Transverse radius

Pre-conditioning of 10 cycles of 100N resulted in separations of 4mm for 6-strand, 5.9mm for 4-strand but 11.5mm in 8-strand repairs, this comprised 48.5%, 68.6% and 72.7% of the separation that occurred after 100 cycles of 100N (Figures 38, 39, 40 and 41).

Figure 38: End-to-end separation with cyclical loading for the 3 repair configurations.

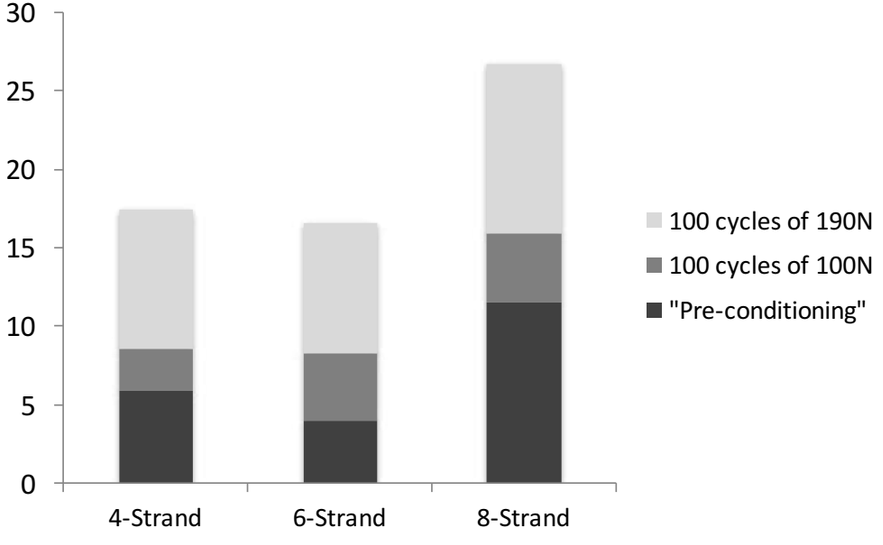


Figure 39, 40 and 41 *(Page 75-76)*: The effect of loading on the repaired bovine tendons. Initial separation, separation after 10 cycles, 100 cycles, 200 cycles and loading to failure. Figure 40 shows knot failure and figure 41 distal pull-out.

Figure 39

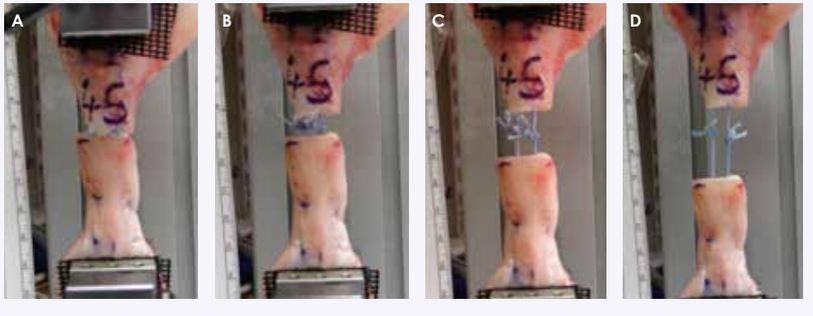


Figure 40

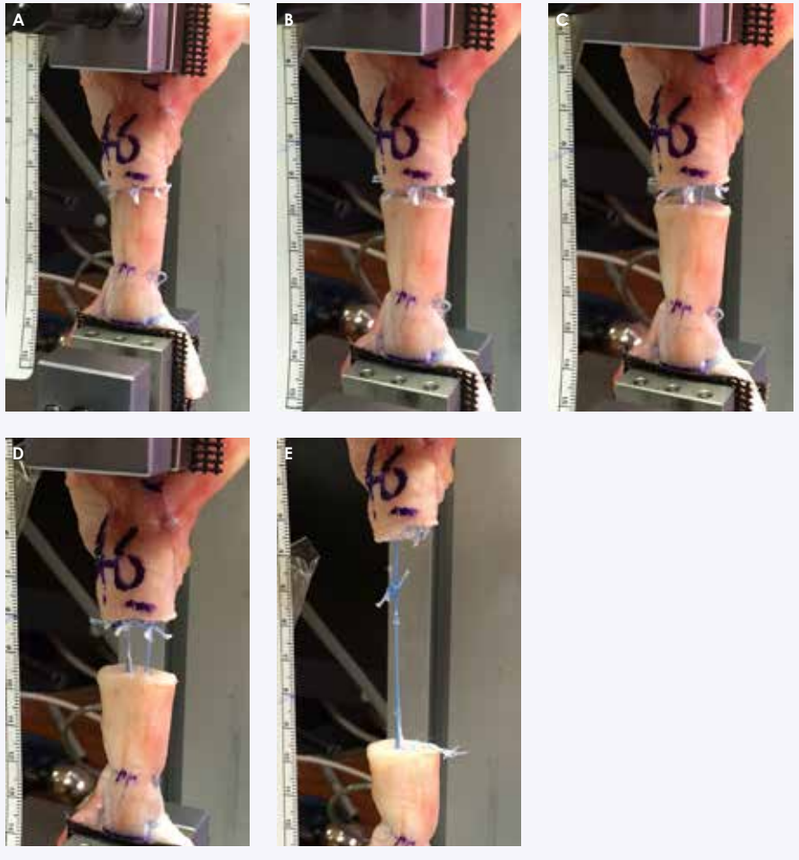
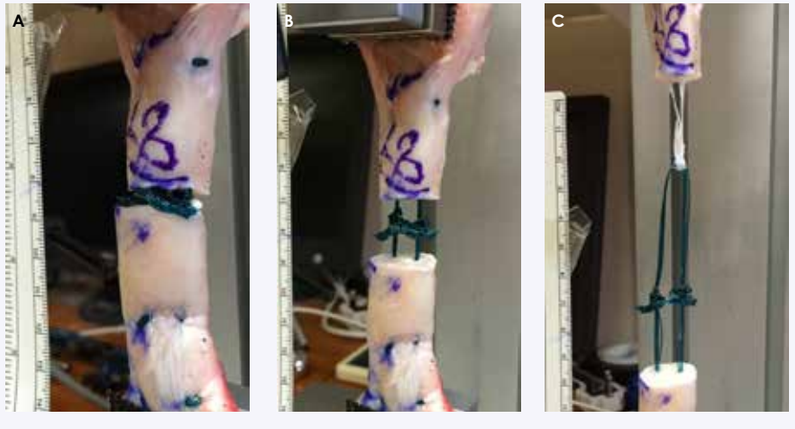


Figure 41



The tendon separation after the third phase of 100 cycles of 190N was 17.4mm for 4-strand repairs, 16.6mm for 6-strand repairs and 26.6mm for 8-strand repairs. Over the four phases of the loading programme there was a significant difference between the different repairs ($p<0.0001$). Four and six strand non-absorbable repairs had significantly less separation than 8-strand absorbable repairs ($p=0.017$ and $p=0.04$ respectively). There were no significant differences between the 4- and 6-strand repairs. When clinical failure was considered to be tendon end separation of ≥20mm all of the 8-strand repairs failed, whereas only one of the 4-strand specimens and none of the 6-strand specimens failed.

Out of the 19 specimens tested, 7 of these resulted in pull-out from the clamps holding the tendons before cyclical loading resulted in ultimate failure of the repair. Regression analysis revealed no significant ($p=0.32$) differences between the ultimate strength of the 3 repair models (4 vs. 6: $p=0.30$, 4 vs. 8: $p=0.87$; 6 vs. 8: $p=0.39$). The mean ultimate tensile strengths (SEM) were for 4-strand 464.8N (27.4), 6-strand 543.5N (49.6), and 8-strand 422.1N (80.5). In all specimens ultimate tensile failure occurred at separation far in excess of clinical failure.

The mode of failure was distal pull-out in 5 (41.7%) specimens *(Table 28)*, proximal pull-out in 3 (20.8%) specimens and knot failure in 4 (33.3%) specimens. Knot failure occurred in 2 absorbable monofilament suture repairs and one of the 4 and 6 strand specimens. There was only one case (in a 4-strand repair), in which the suture failed.

Conclusion:

The use of a non-absorbable suture resulted in less end-to-end separation when compared with absorbable sutures when an Achilles tendon repair model was subject to cyclical loading. Ultimate failure occurred more commonly at the distal Kessler suture end although this occurred with separations in excess of clinical failure. The effect of early movement and loading on the Achilles tendon is not fully understood and requires more research. The use of non-absorbable sutures repair may minimise of end-to-end separation with early loading. Aims to reduce tendon elongation may prevent plantar flexion strength deficits following Achilles tendon rupture.

6. Discussion

Michael R Carmont

The studies in this thesis aim to represent an evaluation of evolving clinical practice. Outcome measures have been conceived, validated and are now used to compare operative techniques leading to improved patient care following Achilles tendon rupture.

The studies comprising this thesis show that the Achilles tendon Total Rupture Score (ATRS) has been cross culturally adapted to the English language, describe and validate the Achilles Tendon Resting Angle (ATRA) and show that percutaneous repair is more cost effective than open repair of the Achiiles tendon. The pattern of change in the ATRA following rupture, repair and rehabilitation of the Achilles tendon for minimally-invasive repair has been determined. There were no differences in clinical outcome between patients receiving repairs performed using absorbable or non-absorbable sutures. The use of non-absorbable sutures led to less separation following repair and during initial cyclical loading.

The Achilles tendon Total Rupture Score

The English version of ATRS is reliable, valid and sensitive to changes over time, making it appropriate to use the score as a patient reported outcome measure following Achilles tendon rupture. The validity of the responses of both the English and Swedish populations was found to be similar suggesting that the ATRS can be used as an outcome measure for studies in these countries.

The effect size in this study was found to be high at 0.93, indicating that the English version of ATRS is sensitive to detect changes over one year of follow-up. In Nilsson-Helander's original study the effect size was between 0.87 and 2.21, and higher values were found between the evaluation at 3 and 6 months. Since these studies used different treatments it is not possible to ascertain whether the differences in the effect size are dependent on the treatment or any differences of the score. While the main importance is that the score is sensitive to changes over time, further analysis needs to be undertaken to determine the clinically important difference. For the ATRS, the minimally detectable change that exceeds the error expected for the measuring instrument was found to be 6.8 points. Therefore for patient groups

treated with different treatments or operative techniques, assessed using the ATRS, a difference of greater than 6.8 points between the two groups suggests this could be due to the different method. This value is useful when using the English version of the ATRS as an outcome measure in future studies and for calculating the the cohort size of future studies. Since this study, the ATRS has been cross culturally adapted to 8 other languages with a MDC ranging from 2 points on a group level in Norwegian to 30 points on an individual level in Dutch [11,68,94,145,213,287,305].

Only minor changes were made to the wording of the original score, tiredness was exchanged for fatigue, ground for surfaces and heavy physical work for hard physical labour but these are important aspects following ruptures of the Achilles tendon. These terms are better understood by the general English population permitting independent score completion, rather than patients requiring assistance or incomplete forms.

Another observed limitation for the score is that it is a subjective report on functional limitation. The expected activity demands may vary between patients following injury, and their sense of limitation may also vary. For example, a young gymnastic instructor commencing rehabilitation following injury may have significant limitation and yet may have what the general population would consider good function. By comparison older retired individuals would rarely perform heavy physical work, jumping or running and so are not particularly limited. For this reason; since the ATRS is a subjective functional score it is recommend it to be used in conjunction with objective functional measures, such as strength measurments and range of motion when evaluating outcome following Achilles tendon rupture.

As an outcome instrument, the ATRS is valuable in clinical patient follow-up. The score allows the physician an immediate representation of the patient's function at a glance. This can be used to reassure patients, particularly at the 3-month follow-up visit and also to indicate the requirement of further physiotherapy at 9-months and occasionally the possible indication for further surgery.

The cost effectiveness of open and percutaneous repair

It was estimated that the costs of surgery for open repair was £935.4 and percutaneous repair to be £574.0. This estimate is comparable to the numbers in Ebinesan et al's.'s study of £1683 for open surgery and £556 for percutaneous surgery [82]. The study of Goel et al. reported a saving of $236,000 over the three years of study recruitment. This represents a saving of $949 per patient, for the 282 patients recruited [100].

The Swansea Morriston Achilles Rupture Treatment (SMART) protocol was introduced in Swansea hospital in south Wales in 2008 [125]. This was a physiotherapy-led treatment protocol where treatment was based upon patient age, complete rupture in the body of the tendon and the gapping of the tendon ends with passive plantar flexion based on ultrasound scanning. Patients fulfilling the first two criteria and with non-opposition of greater than 1cm were advised to undergo operative management, the remainder non-operative. This programme estimated cost savings based upon 55 patients per annum, a yearly saving of £91,000 to the health-care provider [125].

Truntzer et al. performed a cost minimisation analysis of operative and non-operative treatment and found that operative repair was more expensive; $4,292 compared with $2,432 for non-operative treatment [283]. Truntzer et al. explained that the cost savings were based on the payer's perspective rather than the individual or even societal costs [283].

The cost savings in Hutchison et al. and Truntzer et al.'s studies cannot be directly compared to Study II since they have compared operative repair with non-operative management. In Hutchison et al's. SMART programme 62 patients (22.7%) received operative repair. The study does not state the method used, however, open repair had been performed indicating that the use of a percutaneous or minimally-invasive repair could have led to further cost savings.

Study II was performed to compare the functional outcome, complications and estimated costs for the health-care provider of two operative repair options for the management of a ruptured Achilles tendon. The cost of percutaneous repair was estimated to be significantly lower than open repair. This is largely the result of the significantly shorter hospital stay with the majority of patients being managed in a day care unit. This study suggests that percutaneous operative repair is more cost-effective without compromising patient care.

In terms of health-care economy, consideration must be given to patient management where there are complications with increased operative time, hospital stay and clinic visits. The outcome of patients receiving operative repair of the Achilles tendon was good, with minimal number of major complications in both groups. In common with other series, there were increased numbers of sural nerve injury in the percutaneous group, and increased rates of wound breakdown in the open group, but an equal number of infections [100,109]. Due to the high rates of iatrogenic sural nerve injury, the surgical technique has been modified by exposing and protecting the sural nerve, through a small mid-supero-lateral incision, to reduce the risk of nerve injury. Re-rupture rates were similar with one occurring in each group, however, the literature suggests that higher re-rupture rates would be expected with percutaneous repair [99,100]. For health economic analysis it may be considered reasonable to include the functional outcome and costs of management following re-rupture in overall values but since the outcome could not be demonstrated in the open repair group, these were excluded from comparison. Since there was one re-rupture in each group and other complications were similar it is reasonable to consider that these costs are the same.

One patient in the percutaneous group requested removal of the prominent suture knot. The Maxon material resorbs with time, however, the bulk of the knot may take over a year to resorb. There was one case of re-rupture in both groups. One patient suffered from an additional rupture at 6 months following repair in the percutaneous group. This occurred at a separate site at the musculotendinous junction compared with the original mid-portion rupture site. This complication has only recently been reported in the literature with the thickened healing mid-portion rupture site resulting in a stress riser where the healing section meets the tendon towards the musculotendinous junction [249].

The functional outcomes following percutaneous and open Achilles tendon repair have been widely reported in the literature and similar to this study with no difference in outcome [176,301]. The ATRS in both groups were similar (88.8 points for percutaneous repair and 89 for open repair) despite there being a significant difference between the follow-up time periods (Twelve months for percutaneous repair and 49 months for open repair). Patients having percutaneous repair were reviewed until their outcome score reached excellent or good level (ATRS=85) or until 12months following surgery. Given that functional strength significantly improves between one and two years following repair [37,230] it is possible that the comparable function may actually be better in the percutaneous repair group with time. The ATRS was not significantly different in operatively treated patients at 12 months (85 points) and 24 months (90 points) comparable to the scores of 88.8 and 89 points for percutaneous and open repairs in the present study.

In Study II the theatre costs could not be precisely calculated, but were based upon tourniquet time, which was significantly shorter for those undergoing percutaneous repair compared with open repair (open 43minutes vs. percutaneous 15minutes ($p<0.0001$)). These times are comparable with operative times reported in other series [118,177,135]. The duration of outpatient follow-up was considerably longer in the percutaneous group compared with the open group of 8.9 vs. 5 months respectively; however, the overall number of outpatient visits was equal at 5.1. In Ebinesan et al. and Truntzer et al.'s series, patients receiving operative repairs were seen for a mean of 5 and 6.7 visits respectively [82,283].

Diagnosis in both groups was established clinically as described earlier. Ultrasound is not routinely used in specialist practice, however, in general orthopaedic practice requests are often performed. Similar numbers of ultrasound scans were requested per group (open 4 and percutaneous 3). By using clinical assessment rather than routine ultrasound examination considerable cost savings can be made. The ultrasound scanning was

a considerable contributing cost to treatment in the SMART protocol [125] and a recent systematic review by Dams et al. recommended relying primarily on clinical examination and evaluation [72,282].

Specialist management would appear to improve outcome [125] but a recent study has found that although operative times were longer, patients had better outcome when surgery was performed by non-specialised surgeons compared with specialised [272]. It is possible that specialised surgeons used more precise suture configurations e.g. minimally-invasive techniques, which has a learning curve [242], whereas non-specialised surgeons used multiple strands crossing the repair site in an attempt to improve repair strength [272].

Early functional rehabilitation with early weight-bearing, active movement and the use of a functional brace has been shown to improve outcome following Achilles tendon rupture [266]. Physiotherapy plays a key role in the rehabilitation following rupture and the number of physiotherapy appointments should be considered in cost evaluations. In Truntzer et al.'s series, a greater number of physiotherapy visits was required following non-operative treatment compared with operative (12 vs. 7.4) with a significantly less cost in the operative group; $928 vs. $595 [283].

Following this study early specialist consultation for Achilles injury, clinical diagnosis, percutaneous surgery and early-accelerated rehabilitation is recommended to make the operative management more cost-effective. The studied management pathway can been modified so that patients suspected of rupture in the Accident and Emergency Department are placed into a synthetic functional Achilles cast, prescribed thrombo-prophylaxis and then referred directly to a specialist clinic. Patients choosing operative treatment should be managed through a day-care surgery unit.

The use of percutaneous repair under local anaesthesia, with patients managed through a day care unit, and subsequent early accelerated rehabilitation improves the cost-effectiveness of operative management of Achilles tendon rupture. Societal and personal costs could be assumed by early return to work [88,266] although they were not specifically studied.

The longitudinal outcome following percutaneous repair

Study III assessed the longitudinal outcome during the first year following percutaneous repair. Patients reported marked limitation of function by 3 months with a mean ATRS of 42.5, but little limitation of function by 6 months with a mean ATRS of 73, and near good/excellent outcome 9 months following repair, and a mean score of 89 at 12 months following repair. The greatest improvement of function occurred between 3 and 6 months. The success of this method of treatment is similar in younger and older patients, and the timing of repair does not appear to influence the results when performed within 7 days following injury. Percutaneous repair of the Achilles tendon is a reliable and reproducible method of restoring good function with minimal functional limitation.

Several studies have assessed outcome using the ATRS following its development [7,37,147,148,189,191,192,218,229,230,232,253]. One randomised controlled study has compared treatments using the ATRS. Scores at 6 and 12 months were 72 and 88 points for operative repair and 71 and 86 points for non-operative management and these are almost identical to those reported in this series [218]. Olsson et al. reported a similar score of 38 points at 3 months of follow-up and showed that heel rise ability was an important early outcome factor and was reflective of patient-reported outcome and physical activity [231]. Several outcome studies have been performed using ATRS at one time point. Metz et al. has reported follow-up at a mean of 6.2 years post injury with a mean score of 84 points [205]. Maffulli et al. report good outcome in athletes [192], satisfactory outcome in the elderly (ATRS 69.4 points at 7 years following repair) [189], and recently in a small cohort with an ATRS of 84 points at a mean of 26 months following repair [107]. These studies are useful for comparison as they feature a similar operative technique. A randomised controlled study by Olsson et al. showed similar ATRS outcome scores of 44, 75 and 89 points respectively at the 3, 6 and 12 months following repair [230]. These values are almost identical to those reported in Study III.

Möller et al., Twaddle et al., Keating et al., and Patel et al. have all reported on early clinical evaluation at 3 months followed by long-term evaluation [152,208,209,239,284]. Möller et al. have shown incremental increases in visual analogue score and a specifically developed functional index lower limb score [208]. Twaddle et al. assessed their patients at 8 weeks, 6 and 12 months, reporting increasing function using the Musculoskeletal Functional Assessment Index, with a score of 15.2, 7.8 and 3.4 points respectively [284]. In Keating et al.'s study, the Short Musculoskeletal Functional Assessment at 3 months showed better outcome in surgically treated patients ($p<0.03$) [152]. Recently, Patel et al. reported increasing AOFAS scores at 6 weeks, 3, 6 and 12 months following repair with a trend towards statistical significance between the AOFAS Ankle-Hindfoot scale and the time to reach a plateau of improvement ($r=-0.2$, $p=0.06$) [239]. All these scores show similar changes in value during the first year, but Study III was the first to report Achilles tendon rupture specific subjective functional outcome scores at 3, 6, 9 and 12 months following repair using the ATRS.

Silbernagel et al., Olsson et al., Bostik et al. and Brorsson et al. have recently reported that since strength deficits remain at 1 and 2 years following operative management, treatment should be focused on improving function in the first year following operative treatment [33,36,204,260,229,231]. Patel et al. have shown that the functional outcome of patients plateaus out at nine months following surgery [239]. Schepull et al., however, commented that there may be a ceiling effect of the ATRS, which may influence the outcome scores [253]. On-going follow up beyond 12 months and up to 24 months has shown significant improvements in ATRS in non-operatively treated patients (85 to 89 points ($p=0.017$)) whereas patients managed operatively did not report a significant increase in the ATRS (89 to 90 points ($p=0.321$)) [229]. These small improvements may suggest that the ATRS may plateau beyond the one-year time point.

Qeno and Stoianovich commented "Achilles tendon ruptures should be operated on and without delay" [243]. Since then, Carden et al. recommended that repairs be performed within 48 hours of injury to improve outcome [44]. It is generally recommended that percutaneous repairs are performed within two weeks of injury to reduce the risk of adhesion formation to prevent end-to-end juxtaposition. In this series, almost all patients were operated on within 14 days of injury. The outcomes of those operated within 48 hours of injury (n=7) and within 7 days of injury (n=50) were similar. This would suggest that percutaneous repair can be performed on an urgent rather than emergency basis as long as the rupture is protected in a plantar flexed cast or brace.

Achilles tendon ruptures have a bimodal distribution with a first peak of predominantly males in their fifth decade, and a second peak, with a much lower male to female ratio (1.6:1), in the seventh decade [66,189]. This series reflects this with a second peak of predominantly female patients. Bergkvist et al. have suggested that female elderly patients may benefit more from operative intervention [28].

Strengths of Study III are that it reports outcome in a systematic and validated fashion in a large population of patients. To avoid bias based on missing data, the data from the last assessment were carried forward prior to statistical analysis. This method gives a conservative estimate of the outcome at each time points, and still the data were similar to what has been previously reported.

Taken together, following percutaneous Achilles tendon, patients report a marked improvement in function between 3 and 6 months following repair with continuing, but reduced improvement up to one year. The majority of patients reported excellent or good scores beyond 6 months following repair, with ATRS of 89 points at one year. Urgent surgery (< 48 hrs) did not result in improved early or end stage outcome compared with prompt surgery (<2 weeks) for percutaneous repair.

The reliability of Achilles Tendon Resting Angle and Calf Circumference measurements

The main findings of Study IV were that the ATRA and calf circumference measurements were shown to have excellent reliability and as such these methods are recommended for future studies. The ATRA measurement technique could be used as a guide to repair when used

intra-operatively and may be considered to be a method of indirect determination of Achilles tendon length during rehabilitation. The minimal calf circumference at a level 15cm below the antero-medial joint line could be used to give an indication as to the recovery of calf muscle size during rehabilitation. These methods are easily performed, inexpensive and do not require radiation exposure or operator experience. In this series of healthy subjects calf circumferences were found to be symmetrical and therefore the contralateral calf can be used as a guide to muscle wasting.

Uchiyama et al. used the angle between the lateral border of the foot and a line parallel to the operating table termed the Alpha angle with the knee at 90˚ flexion [285]. One hundred patients underwent open repair performed using the Tsuage technique using the alpha angle of the non-injured side to guide the tension of the repair. Although the post-operative alpha angle or arc of movement was not commented upon, 92% of patients had a full ROM by 10 weeks. The remainder improved to have only limited dorsiflexion at 17-25 weeks. Patients were able to perform a double heel rise by 7.6 weeks and a single heel rise by 12 weeks. The importance of having the knee at 90˚ flexion was stressed during the estimation of the Alpha angle [285]. This Alpha angle was also used as an intra-operative guide to the posture of the ankle, termed the Gravity Equinus Position during reconstructions for chronic ruptures [251].

Araujo et al. also used angle between the axis of the fibula and the sole of the foot as a clinical measure for the passive stiffness of the ankle. The tension on the plantar flexors was standardized by hanging a 2Kg mass from the foot 8cm anterior to the lateral malleolus. This angle measurement was validated by comparison with an isokinetic dynamometer. Pearson correlation coefficient ranged from r=-0.81 to -0.88 p<0.001 for passive ankle resistance measured with the dynamometer and the results of the clinical measure of "position of first detectable resistance" [13].

The validity of methods of ankle joint movement has previously been compared. Goniometric assessment of ankle plantar flexion and dorsiflexion has been found to be less reliable (ICC 0.18-0.6) compared with static radiographic images (ICC 0.79-0.83) and measurement using a Hooklying position (0.91-0.92) [220]. The reliability of the Hooklying position was comparable to the reliability of the Achilles Tendon Resting Angle measurement (ICC 0.92).

The purpose of Study IV was to determine the reliability of the measuring technique. A standard goniometer with 2˚ increments and 15cm arms was used in this study. The results suggest that these increments are adequate for measuring the ATRA but for subsequent studies, a goniometer with 30cm arms and 1˚ increments was used, to increase the precision of the measurement. The assessor must ensure the knee is flexed to 90˚ with a neutral subtalar joint to obtain an accurate angle to measure and ensure reproducibility on subsequent measurements for ATRA assessment. In a case study of a patient with an Achilles tendon rupture, it was found that on the injured side where Achilles tendon was elongated the ankle was less plantar flexed with the knee straight (11˚) compared to when the knee was flexed to 90˚ (4˚). On the healthy side the ankle remained in 21˚ of plantar flexion with both the knee straight and flexed. This suggests that increasing ATRA and potentially Achilles length may be revealed when measuring at 90˚ of knee flexion.

Calf circumference has been shown to correlate with muscle volume (R2=0.2, p<0.0001) [248], but not with strength [174] or calf muscle endurance (rs =0.102 (p=0.39)) [209]. Heel-rise endurance rather than single heel rise has been shown to be a predictor of long-term outcome [33,259]. The values of height of heel rise and the number of heel rises may be assessed by dynamometry, the use of linear encoders or laser beam penetration and compared in the form of a limb symmetry index (LSI) [33,37,260]. These assessments may not be possible at the early stages of recovery when patients may not have the ability to perform a single heel rise [36]. Only half of the patients would be able to perform a single heel rise after 3 months [231].

The ATRA and calf circumference at 15cm from the antero-medial joint line are reliable, quick and inexpensive parameters, which correlate with tendon elongation and functional outcome. It is appreciated that the ATRA and calf circumferences may vary throughout the day according to the amount of walking and other activities. This variation is minimised by comparison with the non-injured side.

The variation in ATRA following rupture, minimally-invasive repair using absorbable suture, and rehabilitation

The most important finding of Study V was that the ATRA was found to be an indicator of tendon rupture. The angle increases following injury, is reduced by surgery, and then increases again during initial rehabilitation. This angle may reflect the changes in Achilles tendon length during healing although the relative contributions of tendon length, muscle length, muscle activation, bulk and tension on ATRA have yet to be fully determined. There was no significant difference in the relative ATRA measured in clinic and when measured under general anesthesia, showing the measurement is reliable. Following repair, the reduced relative ATRA, (increased plantar flexion), was maintained in the majority of patients whilst weight-bearing using a protective dorsal shell until 6 weeks. However, the ATRA increased significantly by 3 months following repair. The ATRA also correlated with patient-reported outcome early in the rehabilitation and with heel-rise height after one year and can accordingly be used as part of the outcome evaluation at 12 months.

In studies that have evaluated both the separation of tendon ends and tendon length it has been found that initially there is elongation up to about 3 months followed by a slight subsequent shortening [139,211,222,253]. This pattern of elongation and shortening is similar regardless of treatment such as operative or non-operative treatment and early or late mobilisation. This study supports these findings in that a small increase in ATRA was noted between operative repair and measurement at 6 weeks. A greater increase in ATRA occurred between 6 weeks and 3 months. Thereafter, the ATRA did not significantly change although a small, but non-significant reduction of ATRA was noted at the 12 months time point. The ATRA describes the passive tension from the ankle and possibly other structures around the ankle. The change in ATRA between 6 weeks and 3 months may be the result of tendon elongation after removal of the protective dorsal brace or alleviation of stiffness of the ankle joint. Following brace removal, patients were asked to wear a 15mm in-shoe heel wedge. The increase in ATRA was not prevented by wedge use, although compliance was not recorded. It must be remembered that the post-operative ATRA was recorded following end-to-end apposition of the tendon, under direct vision, before any ankle stiffness had developed. Active plantar flexion exercises were commenced at two weeks following repair and thus the plantar flexion component may have been restored, but not the dorsiflexion component. At this time, it is not known if the change in ATRA is only related to tendon length and there may be contributions relating to muscle tension and improvements in ankle joint flexibility.

During the early stages of recovery; at 3 and 6 months the absolute ATRA correlated well with the patient-reported outcomes score (ATRS). Previous studies have also reported a correlation between Achilles tendon elongation and clinical outcome [139,140].

The patients in Study V had deficits in terms of heel-rise height, which is similar to other studies [229,260]. This measure has been suggested to be an indirect measure of the Achilles tendon elongation following a rupture [260]. One explanation for a lack of correlation is that, although the ATRA was measured with the knee in 90˚ flexion, the heel rise was performed with the knee straight. Further studies comparing actual measurements of Achilles tendon length through either MRI or ultrasound imaging with the ATRA are needed.

Reasons for the increased ATRA include suture resorption/degradation over time, suture cut-out of the tendon, suture failure and an alteration in the Modulus of Elasticity (E) including callus

formation of the healing tendon. In Study V, surgical repairs were performed using 8 strands of # 1 Maxon (Covidien, Dublin, Ireland), a synthetic absorbable polyglyconate copolymer of glycolic acid and timethylene carbonate. In this series, the greatest elongation occurred between the 6 and 12 weeks, possibly indicating that degradation of the suture material could be a factor in the increase of ATRA.

The mode of failure of percutaneous sutures using the Achillon configuration and the configuration used in this series is by suture cut-out of the tendon [180], and this occurs at a significantly reduced loading than failure with open repairs [171]. Failure occurred from pull-out of the Kessler-configuration's distal end [180]. In this technique, the suture material is intra-tendinous rather than extra-tendinous, but within the paratenon, as in the Achillon technique. The presence of the suture may alter the biomechanical properties of the repaired tendon, and this should be born in mind when assessing the Modulus of Elasticity.

Determination of the ATRA to both the injured and non-injured sides is a considerable strength of this technique, as this allows absolute and relative ATRA to be determined. Unilateral tendon elongation determination may vary according to stretch and activity. It may also be determined intra-operatively as a guide to the tightness of the Achilles tendon repair.

Direct visualisation of the apposed tendon ends at the time of surgery is strength of the minimally-invasive technique of the Achilles tendon rupture. Intra-operative measurement of the ATRA allows the resting tone of the ankle to be reduced following repair. The increase in the ATRA beyond that of the opposite side occurred between 6 weeks and 3 months following repair. This may be a key phase of tendon healing to restore normal activities, strengthening of the calf muscle and proprioception of the ankle and yet minimise tendon elongation. Although the ATRA may reflect the resting posture of the ankle, a direct relationship of this angle to the length of the Achilles tendon has yet to be shown. Other factors such as joint capsule stiffness may also influence the resting angle in addition to tendon length.

The functional outcomes of minimally-invasive repair using 4- and 6-strand non-absorbable sutures

The most important finding of Study VI was that there was no difference in outcome for patients whose Achilles tendons were repaired using a 4-strand repair and a 6-strand repair. The 6-strand repair tended to lead to a smaller ATRA following rehabilitation; however the 4- and 6-strand repairs did not show a significantly different ATRA at follow-up. There was no difference in heel rise height between the two groups and a reduced height (80.9%) was found compared with the non-injured side at 12 months. The ATRA at 3 months for both 4-and 6-strand repairs, correlated with the ATRS and HRHI at 12 months.

Additionally the use of a non-absorbable suture during minimally-invasive repair of an Achilles tendon rupture and accelerated rehabilitation did not prevent an increase in relative ATRA. The ATRA was reduced following repair, and then increased during weight-bearing in a protective anterior brace to a similar angle to the non-injured side. Patients commenced active plantar flexion, inversion and non-weight-bearing eversion exercises during this time period. Subsequent increase of the angle until the 3 months time point coincided with weight-bearing, initially minimised by protection with an anterior brace and then a heel wedge. The commencement of wedge use, discontinuation of the anterior brace and the strengthening programme led to an increase in ATRA. After the 3 months time point the angle tended to decrease towards that of the non-injured side.

The degree and progress of ATRA in Study VI in patients repaired using non-absorbable sutures were similar to that in Study V, where the Achilles tendon was repaired using an 8-strand absorbable suture. In Study V the ATRA was reduced to 7˚ following operative repair, then reduced with weight-bearing in the brace to 2.6˚. Subsequently the ATRA increased at the 3 months time point to -6.5˚ and was at the 12 months follow-up -4.7˚.

Although there were no differences in mean outcome between the use of 4-strand and 6-strand non-absorbable repairs, the proportion of patients receiving a 4-strand repair who had an ATRA ≥12˚ was almost twice that having a 6-strand repair at the 3 months time point, however, this had fallen to 1.5 times by the 12 months time point. Thus the decision to increase the number of strands did not influence the mean outcome but did reduce the proportion of patients who had an increased ATRA. A similar progression of ATRA has been seen using an 8-strand absorbable repair. This suggests that repairs using more suture strands may be less likely to have an increased ATRA. It may be that differing suture configurations and in particular locking sutures may have greater resistance to elongation. Conversely, it is noted that with a greater quantity of suture material and a tighter, presumably stiffer repair, may have less favorable long-term biomechanical properties [252,254].

The ATRA reflects the resting posture of the ankle, but a direct relationship of this angle to the length of the Achilles tendon has yet to be shown and future imaging studies are needed. Extended field of view ultrasound imaging has been shown to be a reliable and valid method of determining calcaneal to gastrocnemius length (ICC 0.895, SEM 0.67) [261]. In cadaveric studies, Costa et al. have determined that 10mm of tenotomised tendon end separation corresponded to a 12˚ increase in ankle dorsiflexion 64 and it is reasonable to compare this to lengthening of the Achilles tendon. It was for this reason that ≥-12˚ angle change, corresponding to ≥1cm elongation, was chosen as a threshold for comparison of predictability of repair [253].

The 12 months findings of a relative ATRA of 5.5˚ and a HRHI of 80% are almost identical to a recent series of non-operatively treated patients [84]. In Ecker et al.'s study patients were protected for a longer time period using a 20˚ equinus weight-bearing cast for the first 6 weeks and then a boot with heel wedges of diminishing height until 12 weeks. In all patients studied in this thesis a brace was used for 6 weeks with a 15mm heel wedge until 3 months. Using steel suture markers Cetti et al. reported a significant elongation of 6.3mm during this time period [54]. The change in ATRA relates to the period of early weight-bearing and early mobilisation suggesting reconsideration of the concept of early rehabilitation.

The outcomes in this study are similar to symptoms reflected by the ATRS in several other studies [7,230,253] and function in terms of HRHI, except for at the 3 months time point when only 30% of patients could perform a single heel rise compared with 50% in Olsson et al.'s study [232]. The reason could be differences in the rehabilitation or patient evaluation. In Olsson et al.'s study the evaluation was performed after a warm-up exercise period, including double heel rises, prior to assessment.

One of the limitations of Study VI is that it is not a rigorously designed randomised controlled trial. A RCT would provide an answer as to determine the differences between 4-strand and 6-strand repairs. The strength of this study is its pragmatic nature evaluating the outcome of current practice and utilising simple, easy and inexpensive outcome measures that can easily be adopted in the clinical setting. It is possible that the suture technique may be important in the early stages of healing following repair to preserve intra-tendinous tension. The aspects of duration of brace protection whilst weight-bearing and the timing of loading commencement to prevent elongation require further investigation.

Several studies have compared repairs performed using absorbable and non-absorbable sutures [20,54,131,159,195]. Yunhan et al. have compared the outcomes of tendon ruptures repaired using PDS and Ethibond open Bunnell sutures. Patients reported AOFAS scores of 93 and 97 points at 3 months, with no difference in complication rates [131]. Marican et al. performed a retrospective study on 60 patients with different sutures used. The authors found no association with the type of sutures used and wound infection. Twelve percent of patients had superficial wound infection and 5% deep infections. Of these two had deep suture granulomas removed and one underwent an open debridement and required secondary procedures [195].

Tendon end separation with loading: a comparison of non-absorbable and absorbable sutures

The most important finding of Study VII was that repairs performed with non-absorbable braided

sutures resulted in less separation than with absorbable monofilament sutures, when subjected to a loading protocol. The separation of tendon ends when subjected to 100 cycles of 100N loads was less than 1 cm when specimens were repaired with the non-absorbable suture. When loads of 190N were applied for 100 cycles, the non-absorbable repair models had 16.5mm of separation, whereas the absorbable suture repairs resulted in clinical failure (≥20mm) or ultimate tensile failure.

Although the two loading protocols are considered to be consistent with walking in a brace with a 2.5cm heel raise and passive range of movement exercises, the quantitative separation reported in this study is not directly applicable to patients for number of reasons. Firstly the bovine tendons were larger than those in patients, they did not have pre-existing degeneration [55,134,136,190] and technically an open repair rather than a percutaneous repair of the dissected specimens was performed. This study was to compare suture configuration inserted using a percutaneous/minimally-invasive technique. The differing superficial soft tissues between human and bovine Achilles tendons necessitated that specimens were dissected free from superficial soft tissues. The sutures were subsequently placed as an open repair eliminating the confounding variable of poor suture placement, which can occur in using a percutaneous placement [117]. In Heitmann et al.'s study, 3/10 specimens had sutures, which passed superficial to the tendon when the Achillon jig was used to guide suture passage [117]. The favourable separation and failure characteristics of the 6-strand non-absorbable suture over the 8-strand absorbable suture shown in this study can, however, be applied to the management of Achilles tendon ruptures in patients.

Another finding of this study was the importance of "pre-conditioning" of the suture configuration prior to knot tying. In this study approximately half of the separation (68.6% 4-strand, 48.5% 6-strand and 72.7% 8-strand) occurred during the first 10 cycles of 100N *(Figures 39b, 40b and 41b)*, compared with the separation that had occurred by 100 cycles *(Figures 39c, 40c and 41c)*. The aspect of pre-conditioning was highlighted in Clanton et al.'s study when 9.5mm 77.9% of the overall 12.2mm elongation occurred during the first 10 of 250 cyclic loading of 20-100N [62]. By comparison when pre-conditioning was applied prior to knot tying Demetracopoulos et al. found a 1000 cycles 20-100N were required to produce 5mm of separation in Achillon and Percutaneous Achilles Repair System repairs [76]. It is recommended that pre-conditioning of at least 10 firms pulls should be applied to the sutures in the proximal and distal tendon ends before the sutures are tied during operative repair.

The use of the digital camera permitted the characteristics of failure to be observed and commented upon. With increased loading, usually in the loading to failure phase, the proximal tendon shortened slightly and appeared to bulk up as the suture tightened, i.e. the accordion effect. In vivo, the consequences of this shortening effect may be minimised by pre-conditioning and then ensuring tendon end-to-end apposition with knots tied with the ankle placed in plantar flexion compared with the non-injured ankle. This operative "over-tightening" compensates by subsequent elongation with loading, movement and remodeling. Another biomechanical property observed was that the absorbable sutures were notably more elastic than the non-absorbable sutures with more stretching and recoil rather than that observed with the stiffer non-absorbable suture. This elastic nature of absorbable monofilament repair may be functionally beneficial in avoiding stress shielding of the repair although this must be considered against knot stability and pre-conditioning characteristics.

In terms of ultimate failure of the repair models, the 6-strand non-absorbable repair had the highest ultimate tensile failure. It is interesting to note that clinical failure; ≥20mm of separation occurred in all specimens prior to ultimate tensile failure. Twenty millimeters of separation was chosen as this was the tendon lengthening noted to occur following non-operative treatment in Heikkinen et al.'s studies [115,116]. Such lengthening would confer no advantage over operative treatment. The commonest mode of failure was distal pull-out of the Kessler suture in 5(41.7%) cases, which is in concert with previously reported failure patterns [180]. Thirty-three percent of the failures were due to knot failure and half of these (n=2) occurred in the absorbable 8-strand suture. The tying of the 8-strand monofilament knots noticeably had greater friction than the PTFE coated braided sutures. One hitch of absorbable suture was noted to untie during the loading sequence although knot failure occurred equally in absorbable and non-absorbable sutures. In vivo, the suture knots are surrounded by healing tendon end and so may be less prone to unraveling with movement at the two-week time point.

Further research is needed in terms of the stability of early repair, avoidance of repair separation, tendon lengthening and yet the maintenance of elasticity to optimise resumption of biomechanical characteristics. The avoidance of tendon lengthening, the reduction in ATRA and the restoration of normal gastrocsoleus strength and Achilles tendon viscoelastic properties are important aspects in recovery from an Achilles tendon rupture.

Clinical course

Knowledge of the normal course of recovery during rehabilitation and expected variations are important factors to consider in the management of patients following an Achilles tendon repair. At the 3 month time point approximately a third of patients reported pain beneath the heel, which has been attributed to the plantar fascia receiving unaccustomed loading in the presence of a weak calf muscle.

The traditional complication, and commonly a primary outcome measure, is re-rupture. The overall rate; 4 patients sustained re-ruptures in the 169 patients studied this thesis was 2.4% *(Table 30)*, which is similar to the majority of minimally-invasive and percutaneous repair series in the literature. There was no difference in re-rupture rate between those having a repair performed using an absorbable suture vs. non-absorbable and no difference in the number of strands of non-absorbable sutures used. Both patients who sustained re-rupture in repairs performed with non-absorbable repairs, did not comply with the usual post-operative mobilisation and safety regime, however, it is acknowledged that compliance could not be exactly monitored. Metz et al. have studied the effects of complications following minimally-invasive Achilles tendon repair and those who sustained re-rupture had a significantly lower ATRS of 71 points compared with 89 points in uncomplicated cases [206]. Although re-rupture did not affect resumption of professional life, the relative risk for quitting sport or resuming sport at a lower level after re-rupture was 3.33 (95% CI 1.71-6.51 p=0.0001). Interestingly plantar flexion strength deficit was only 5% - 10% in the re-rupture group following reconstruction compared with up to 20% in the reference group [206].

Future analysis is required to determine a weight threshold for the repair technique used and the acceptable size of a distal tendon stump suitable for suture placement. A short distal stump is easily recognised clinically as the ruptured tendon end is subcutaneous at this level. The long-term outcomes of new techniques such as direct bone insertion into the calcaneum rather than the use of a transosseous tunnel are awaited.

One of the commonly reported risks of minimally-invasive and percutaneous repair is iatrogenic sural nerve injury. Careful review of the literature shows an injury-related sural nerve rate of 11% (7/66) prior to surgery in Lim et al.'s 2001 comparative study [177]. Sural nerve injury did not significantly affect functional outcome in Metz et al.'s study [206]. Klein et al. and Majewski et al. have recommended exploring and protecting the nerve during repair [157,193]. In Klein et al.'s study, in which repairs were performed using the Ma and Griffiths technique, the mid-lateral incision was extended from a stab incision to 2cm to allow the nerve to be explored. This abolished iatrogenic nerve injury, compared with 13% in repairs performed pre-exploration [157]. In Majewski et al's study compared cohorts of patients in whom the nerve was exposed and protected or not. There were no sural nerve injuries in the nerve exposed group compared to an 18% nerve injury rate when the nerve was not exposed. All nerve injuries occurred in patients where the nerve was not explored and protected [193]. The introduction of sural nerve exposure in the present thesis reduced the

incidence of iatrogenic injury from 6.3% to 1.9%, with no wound issues relating to the small 2cm exploratory incision *(Figure 14)*. Subsequently one patient reported sural distribution anaesthesia at the two weeks follow-up and this had completely alleviated by the 6 week appointment.

The overall infection rate in this Thesis of 2.4% is similar to any foot and ankle procedure. This infection rate was reduced from 2.6% to 2.2% by a change in prophylactic antibiotic from Cefuroxime to Flucloxacillin. The actual rate of infection reduced with the adoption of non-absorbable sutures from 3% to 1.4%. No patients required suture removal on account of infection.

A recent prospective cohort study compared the outcome and complications of repairs performed using absorbable and non-absorbable sutures. Tendons were repaired using an 8-10cm medial incision using a modified Kessler suture with a nylon circumferential running suture. 3.2% patients repaired using the non-absorbable suture, had wound infection and 68.5% of patients reported excellent or good outcome scores. There were no infections and 100% of patients reported excellent or good outcomes in the group repaired using an absorbable suture [20]. Two patients requested surgery for the removal of prominent knots and release of adhesions. Although knots tied using 6-strand repairs are sizable, these can be pushed deep to the tendon and the change from a percutaneous to a minimally-invasive repair permitted closure of the fascia cruris. This may encourage the knots to remain deep and also optimise blood flow in the paratenon layer. Knotless repairs have been shown to be stronger than those with knots [62,65,142], however, the cost of suture anchors must be considered, together with the requirement for general anaesthesia, and the influence of the repairs on the long-term tendon stiffness and biomechanical properties.

The incidence of Deep Venous Thrombosis (DVD) appears to be increasing. Ultrasound studies of the incidence of DVTs have found this to be as high as 34% following rupture. Of these 68.8% were asymptomatic [217]. In Mackdom et al.'s study an incidence of 23.47% was reported and a third of these were noted prior to surgical repair [184].

The overall symptomatic DVT rate in this thesis of 6.5% is comparable to the incidence of 7% reported in Calder et al.'s study [42]. The prophylaxis regime is of 2 weeks of low molecular-weight heparin, covering patients until the posterior aspect of the orthosis is removed and active movements are commenced. Patients are permitted to bear weight early following repair further reducing risks. In Lapidus et al.'s RCT no reduction of the incidence rate was noted with the use of 6 weeks of low molecular-weight heparin 34% in the treatment group versus placebo 37% [167].

In terms of reduction of complications, further research is required in the management of patients with a high BMI and the use of strategies to recognise and treat venous thromboembolic events.

Treatment should focus on patients' individual requirements in terms of physical activity, especially physical competition together with an explanation of the risks of injury and treatment, most important the incidence of thromboembolic events, sural nerve injury and skin complications and other infection.

7. Limitations

Michael R Carmont

There are several limitations to this thesis.

The first is that in Study I the PROM/ATRS scores were collected in clinic rather than in a neutral setting. This may have influenced patient's responses, however, patients were asked to complete the responses as accurately as they could as this information was used to see how they were progressing and to guide future treatment options.

The completion of the scores in clinic has the advantage of patients being able to ask for advice if they were uncertain and this in turn may have made responses more complete and accurate.

Patients were given a copy of the ATRS score to complete on arrival in clinic, to be completed whilst waiting to be seen and in at the end of their consultation for test-retest comparison in Study I. This means that the test-retest was only the waiting time and time of the consultation, which was typically 20-30 minutes. This short time period may have influenced the results, however, having patients wait in clinic to increase this time would be unnecessary, require explanation and bias encouraging them to reflect on their responses. The short test-retest interval has the advantage of reproducing scores, which may not be susceptible to day-to-day variation. The distraction of the consultation may also have influenced responses and answer recall bias. For all responses there were no significant differences between the first and second scores for each time period. By comparison, in the original ATRS article, a significantly higher score was reported on the second test occasion, compared with the first, when testing was performed twice within two weeks [215]. Another limitation of the test-retest is the surprise factor of the second re-test. Longitudinal analysis of the same patient potentially introduced bias.

In Study II, a comparison study of percutaneous versus open repair, two groups of patients were compared using mixed methods. Patients who underwent percutaneous repair were compared with outcome analysis and retrospective complication analysis of previously performed open repair.

The open repair group could be considered to feature a degree of selection bias as they were patients who requested operative

intervention, hoping for improved function and reduced re-rupture rates. Conversely patients in the percutaneous repair group chose to have repair with complication risks quoted from rates in the author's series.

Loss to follow-up is another limitation of Study II. In the open repair group only 18 (51.4%) patients received PROM assessment compared with 47 (96%) patients in the percutaneous repair group. This may well be a common feature of evaluation studies comparing or auditing the outcome of introduced methods. To ensure standardisation of follow-up a further 6 patients were excluded from analysis in the percutaneous group as final review occurred at less than one year following surgery. Another limitation of this study is that the cost of re-rupture and the societal costs of prolonged absence from work were not included in the calculations.

Studies III, V and VI assessed the longitudinal functional outcome of patients treated with percutaneous and minimally-invasive repair of Achilles tendon rupture.

The most important aspect of this pragmatic research design is to evaluate patient outcome in a clinical setting. This type of design introduces a bias since the surgeon collected the data rather than having an independent observer. This method, however, allowed elimination of inter-observer bias and may improve response rates. Additionally in this Thesis, although data was collected prospectively patients were not randomised into different treatment groups in the different studies. Since the same inclusion and exclusion criterion used for all studies, these studies allow comprehensive cohort comparisons between percutaneous and minimally-invasive repair, absorbable and non-absorbable sutures and finally repairs using different numbers of suture strands. It is interesting to note in Study V that although 4-strand repairs were discontinued out of concern for several patients having an increased ATRA the mean values of 4-strand repairs showed less increase than the later performed 6-strand repairs.

One limitation of the thesis for general orthopaedic research is the absence of a non-operatively managed cohort of patients. The importance of assessment at 2 weeks has recently been highlighted. Those who have tendon gaping or increases in ATRA at 2 weeks receive additional counsel of the importance of operative apposition of the tendon ends. This forms part of established management pathways [84,125]. This knowledge may lead to more patients selecting non-operative treatment initially.

Another limitation relates to the functional scoring of patients at three months following operative management. Two of the questions asked in the modified ATRS relate to the patient's limitation with running and jumping activities. In the rehabilitation protocol used, patients were asked to walk as comfort and confidence allowed but to avoid plyometric exercises such as jumping and sprinting until after three months. Although many studies claim that their athletes return to play within 6 months [192], a consensus of experienced surgeons has stated that this is not recommended until 6 months. Three months is the time duration of a cycle of collagen healing and maturation; therefore, this was selected as a suitable time period to allow re-modelling to occur. Olsson et al. found that, at this time point, i.e. 3 months following repair, only half of patients were able to perform a single leg heel rise [231]. As the ATRS allocates two questions worth a total of 20 points for running and jumping, patients reported limitation in this score for these questions based upon their current activity.

One potential imitation of Study IV is that the included subjects were younger than those typically sustaining Achilles tendon rupture. The purpose was, however, to determine the reliability of the measuring techniques rather than a standard ATRA for a normal population in the peak range typical of rupture. Additionally a standard goniometer with 2˚ increments and 15cm arms was used in this study. The results of the study suggest that these increments are adequate for measuring the angle. For subsequent Studies V and VI, a goniometer with 1˚ increments and 30cm arms was used to increase the precision of the measurement.

Limitations of Studies V and VI are similar to those of Study III relating to the completion of the ATRS. Study V includes a limited cohort but sample size calculations were performed to determine the group cohort sizes in Study VI. Further limitations include a lack of randomisation and an unbalanced design in Study VI, with only 19 patients in the 4-strand group.

Additionally, the progressive developing nature of the assessment process means that HRRI was only performed in patients in Group 2 of Study VI. The use of a more accurate Muscle-Lab assessment to determine Heel-Rise Endurance rather than the simple HRRI may reveal a correlation with ATRA in future studies. The absence of a direct measure of tendon length such as using MRI or ultrasonography, and an accurate determination of heel-rise work and endurance are also considered limitations of Studies V and VI.

There are a few limitations to Study VII; a biomechanical study of bovine tendons. Many of these relate to the tenotomy model, which is used in many biomechanical aspects of Achilles tendon research.

Pilot testing using ovine tendons found these to be too short to reproduce the repair model using the actual surgical needles and sutures to perform the repair. As a consequence larger bovine flexor tendons were used. These specimens were visibly of similar dimensions to the human Achilles tendon.

One limitation of common with others biomechanical testing studies was the ability to secure the tendon in a clamp during the cyclical loading protocol [300]. Several different clamps and grades of sandpaper wrapped around the tendon were attempted during the pilot study to secure the tendon. Finally, the method of removing flexor muscle belly, compression of the tendon end in a vice and wrapping in sanding mesh prior to being secured in the clamp was found to be most effective and this was used in all specimen tests. Despite this, loading of 7 out of the 19 specimens lead to pull-out from the clamp. Four of these occurred at loads ≥400N, however, all had failed clinically (≥20mm separation) by this point.

The use of a "clean" tenotomy rather than a mop head produced during rupture may actually prevent the accurate reproduction of an in vivo repair due to the interposed suture knots. The flat tendon end may prevent shortening of the tendon at repair due to the knots between the apposed tendon ends at the repair site. Artificial mop ends have been applied to tenotomy models [19,101], this may permit shortening of the tendon by mop end-to-mop end apposition. The knots are then buried during repair, within the mop ends and may not prevent shortening. Subsequent elongation and "separation" with loading would restore normal length. The flattened tendon ends, however, permitted more accurate measurement of separation using the vernier caliper. The absence of a stable calcaneus may have also prevented pre-conditioning and the repair from being in as much tension as possible; however, since this factor was consistent for all specimens, this would not influence the outcome of Study VII.

The dissection of tendons free from paratenon and crural layers allowed optimal suture placement and clear looping of the suture outside the tendon potentially increasing the strength of the repair. Although monofilament is considered to slide through the tendon tissue more smoothly than a braided suture, it was also found to have greater friction between the strands than the PTFE coated braided suture. This may have had an effect on both the ability to exert tension throughout the suture configuration and tighten knots.

8. Conclusions

Michael R Carmont

The English version of ATRS is reliable, valid and sensitive to changes over time, making it appropriate to use the score as a patient-reported outcome measure following Achilles tendon rupture.

Percutaneous repair of the Achilles tendon resulted in reduced costs and yet has comparable outcome and complication rates to open repairs. Percutaneous repair should be considered as the primary method of cost-effective operative management of Achilles tendon operative rupture.

Patients marked improvement in function between 3 and 6 months following percutaneous repair of Achilles tendon rupture, with continuing, but less steep improvement up to 1 year following operative management. The presence of a complication did not affect the end-stage outcome.

The ATRA and calf circumference at 15cm from the antero-medial joint line are reliable, quick and inexpensive parameters, which have the potential to correlate with tendon elongation and functional outcome.

The ATRA increases following injury, is reduced by operative repair and then increases during initial rehabilitation. The angle also correlates with patient reported symptoms early in the rehabilitation phase and Heel-Rise Height after 1 year. The ATRA might be considered to be a simple and effective means to evaluate Achilles tendon function one year after the rupture.

Increasing the number of suture strands from 4 to 6 does not alter the ATRA or HRHI following minimally-invasive Achilles tendon repair. The use of a non-absorbable suture during minimally-invasive repair when used together with accelerated rehabilitation did not prevent the development of an increased relative ATRA. The ATRA at 3 months following operative repair correlated with heel-rise height at 12 months.

The use of a non-absorbable sutures resulted in less end-to-end separation compared with absorbable sutures when an Achilles tendon repair model was subject to cyclical loading. Ultimate failure occurred more commonly at the distal Kessler suture end, but this occurred with separations in excess of clinical failure. The effect of early movement and loading on the Achilles tendon is not fully understood and requires more research.

9. Future perspectives

Michael R Carmont

The management of Achilles tendon ruptures has advanced significantly over the last decade with considerable gains in the knowledge of management techniques particularly bracing, and operative repair techniques. Operative repair offers reduced tendon lengthening and improved strength and function.

The ATRA is a simple, reliable, reproducible, responsive and inexpensive method of assessing the functional tension in the gastrocsoleus complex and as such is suitable for registry utilisation. Further work is required to compare ATRA with tendon length.

Further work needs to be undertaken to better understand the importance of the restoration of the viscoelastic properties of the healing tendon to optimise gastrocsoleus function. Minimally-invasive repair may offer similar functional outcome with that of open repair but the techniques used in this series in common with other studies do not offer a stable repair and require protection during early weight-bearing [74].

A post-operative brace was used by all patients in this series and prolonged brace use during at risk activities is now an established method of reducing re-rupture rates [125]. The use of a brace may be acceptable to some, but others may be keen to return to work and other activities without a brace restriction and also avoid re-rupture and lengthening risks.

The confidence of distal calcaneum fixation has contributed to the practice of brace-free rehabilitation [12,81,106,130,133,207,303] and with the improvement in repair techniques and suture stability, this may become the gold standard of management in the future.

Additionally, the importance of restoration of the tendons viscoelastic properties is being appreciated and this must be offset against the potentially increased stiffness of stable repairs.

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Michael R Carmont

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