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# Does an acute Achilles tendon rupture become a patient's Achilles heel in the long-term?

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# Abstract

It is unknown if deficits in the involved limb following acute Achilles tendon rupture (AATR) persist in the long-term, or differ between patients treated operatively or non-operatively. This study investigated 43 patients 15±1 years post-AATR from a previous randomized controlled trial (RCT) that compared operative and non-operative treatment. Structural characteristics in the Achilles tendon and surrounding musculature were assessed using magnetic resonance imaging. We also performed physical examinations and evaluated performance-based and patient-reported outcomes. Overall, there were substantial differences between the involved and uninvolved limbs in most outcomes. Some outcomes improved over time from the initial RCT to the final follow-up, while others deteriorated. No outcomes favoured operative over non-operative treatment.

# Lay Summary

Tendons connect muscle to bone. The Achilles tendon attaches your calf muscles to your heel bone, and is largest and strongest tendon in the human body. Despite these qualities, the Achilles is the most commonly ruptured tendon in the adult population, and has the potential to be a devastating injury. An Achilles tendon rupture can be treated with surgery or conservative care (e.g. physiotherapy); however, not much is known about the long-term effects following either treatment. This study evaluated patients 15 years following rupture. There were substantial differences between the injured and non-injured limbs. Some measures improved over time since the initial rupture, while others deteriorated. We did not find any evidence that surgery is better than conservative care.

# Extended Abstract

**Background:** Long-term outcomes after treatment for acute Achilles tendon rupture (AATR) are unknown.

**Objectives:** 1) To compare involved and uninvolved limbs >10 years after treatment for AATR, 2) To describe changes from 2 to >10 years after AATR, and 3) To compare patients treated operatively and non-operatively.

**Methods:** We recruited 43 participants (20 operative, 23 non-operative) from a previous randomized controlled trial 15±1 years post-AATR. Measures included: structural characteristics in the tendon and surrounding musculature evaluated using 3-Tesla magnetic resonance imaging (MRI); calf circumference and plantar- and dorsiflexion range of motion assessed with physical examination; performance-based outcomes (maximum single-legged heel-rise repetitions and vertical jump height, plantar- and dorsiflexion isokinetic strength, plantar- and dorsiflexion angles and moments during walking using 3-dimensional gait analysis); and patient-reported outcomes (Achilles Tendon Total Rupture Score (ATRS) and Leppilahti Score). We compared involved and uninvolved limbs (dependent samples t-test) at the final follow-up, described changes from the 2-year to final follow-up (two-factor analysis of variance), and compared patients treated operatively and non-operatively (independent samples t-test). Post hoc analyses were conducted to explore the associations between involved limb MRI and performance-based outcome measures

**Results:** On MRI the involved Achilles tendon was thicker and longer; calf musculature cross-sectional area and calf circumference were smaller. Plantarflexion range of motion was higher and dorsiflexion range of motion lower in the involved limb. The involved limb maximum single-legged heel-rise repetitions and vertical jump height were lower. Plantar- and dorsiflexion isokinetic strength were not consistently weaker in the involved limb at final follow-up. There were no differences in plantar- and dorsiflexion angles and moments during gait. From the 2-year to final follow-up, the involved limb experienced decreased active plantar- and dorsiflexion range of motion and increased plantarflexion torque at 60°/s and 240°/s. Calf circumference and the Leppilathi score did not change over time. The Leppilahti score favoured non-operative treatment. At final follow-up, the non-operative group achieved

a higher ATRS. No outcome measures suggested better long-term outcomes for patients treated operatively. Several low to moderate positive correlations between the involved limb MRI and performance-based outcome measures were found.

**Conclusion:** Substantial side-to-side differences in structure and function persist beyond a decade after AATR. Select outcomes varied over time; however, some improved while others deteriorated. There were no outcomes that favoured operative over non-operative treatment.

# Keywords

Achilles tendon, rupture, long-term follow-up, operative, non-operative, accelerated functional rehabilitation, magnetic resonance imaging.

# Co-Authorship Statement

This study was designed by Ms. Michaela Khan (MK) and Drs. Trevor Birmingham, Dianne Bryant, and Kevin Willits. Khan was responsible for patient recruitment, scheduling, data collection and analysis. Magnetic resonance images were analyzed by Khan and Dr. Alison Spouge (AS). Original manuscript was prepared by Khan with guidance from all co-authors. This project was supported by the Transdisciplinary Bone & Joint Training Award, Centre for Functional and Metabolic Mapping Internal Funding Program, and the Brain Canada Platform Support Grant.

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*"Gwell dysg na golud"*

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# Chapter 1

## 1 Introduction

The Achilles tendon (AT) attaches the posterior lower leg musculature to the heel bone, enabling plantarflexion and knee flexion in order for humans to walk, run, and jump. Although the AT is the largest and strongest tendon in the human body, it is also the most frequently injured tendon in adults. The incidence of acute AT ruptures (AATR) increased by 163% in Ontario from 2003-2013, and similar rates have been reported in Europe (Leppilahti et al., 1996; Möller et al., 1996; Schepsis, Jones, & Haas, 2002; Sheth et al., 2017; Suchak et al., 2005).

The healing process in the AT and surrounding tissues is an arduous process. Studies reporting <3-year outcomes have reported side-to-side differences in calf circumference (Cetti et al., 1993), heel-rise height (Olsson et al., 2011; Nilsson-Helander et al., 2010; Silbernagel, Steele, & Manal, 2012), heel-rise work (Olsson et al., 2011; Nilsson-Helander et al., 2010), heel-rise repetitions (Olsson et al. 2011), and drop countermovement jump height (Olsson et al., 2011; Nilsson-Helander et al., 2010). Other studies have shown clinical, functional, and structural deficits in the injured limb may persist beyond 3 years post-rupture (Hufner et al. 2006; Krueger, Siebert, and Scherzer, 1995; Rosso et al., 2013).

Treatment options for an AT rupture can be broadly classified into operative and non-operative management, and there is considerable controversy regarding which technique is optimal. Surgical repair was once considered the gold standard treatment due to a reported lower risk of re-rupture; however, numerous clinical trials have refuted that claim (Carmont et al., 2011; Khan et al., 2005; Willits et al., 2010). The tendency towards surgery has been challenged by the introduction of accelerated functional rehabilitation programs that encourage early weight-bearing and range of motion exercises. Randomized controlled trials and subsequent systematic reviews suggest there is no difference in outcomes after operative and non-operative care if such a protocol is implemented (Nilsson-Helander et al., 2010; Ochen et al., 2018; Willits et al., 2010).

Undergoing surgery also increases the risk of complications such as infection, tendon adhesion, and delayed wound healing (Carmont et al., 2011; Khan et al., 2005). Engaging in early controlled joint mobilization and weight-bearing can reduce stiffness and local swelling, and decrease muscle atrophy (Zhou et al., 2017). As such, accelerated functional rehabilitation has been linked with higher patient satisfaction and earlier return to function (Zhao et al., 2017). Although these deficits may occur in patients treated operatively and non-operatively, no study has directly compared long-term outcomes between the two treatments.

A multi-centre randomized clinical trial by Willits et al. (2010) compared patients with AATR treated with surgical repair and accelerated functional rehabilitation or accelerated functional rehabilitation alone. Re-rupture rate and functional, clinical, and patient-reported outcomes were similar between the groups 2 years post-rupture. However, the potential long-term deficits between limbs, and the potential differences between treatment groups, remain unknown. Therefore, objectives of the present study were to: 1) compare involved and uninvolved limbs ≥10 years after treatment for AATR, 2) describe changes in the involved limb and side-to-side differences from the 2-year to the final follow-up, and 3) compare outcomes of patients treated operatively and non-operatively.

# Chapter 2

# 2 Literature review

## 2.1 Anatomy of the Achilles tendon

The AT is the largest and strongest tendon in the human body. It is primarily composed of tightly woven, longitudinally orientated collagen fibres (90% type I), a material believed to be the primary load bearing component in mature tissue and demonstrating high strength in the direction of fibre alignment (Jozsa & Kannus, 1997). Accounting for only 2% of the tendon's dry mass, the AT owes its elastic properties to the presence of elastin (Henninger et al., 2013; Jozsa & Kannus, 1997). The combination of these two materials, bound in a proteoglycan-water matrix, contributes to the tendon's spring-like properties and its ability to respond and adapt to loading environments. Highly resilient, biomechanical models have predicted the AT can withstand loads of 3.9 and 7.7 times body weight during walking and running, respectively (Giddings et al., 2000).

The gastrocnemius and soleus muscles (collectively known as the triceps surae) combine at the mid-calf region to form the origin of the AT, which inserts distally into the calcaneus. The triceps surae contract concentrically to plantarflex the ankle joint. Superficially, the medial and lateral heads of the gastrocnemius originate from the distal medial and lateral femoral condyles, respectively (Standring & Gray, 2005). Primarily composed of fast twitch muscle fibres, this fusiform muscle is responsible for explosive movements such as during running and jumping. In contrast, the soleus is a slow twitch muscle that plays a vital role in walking and postural control. It lies deep to the gastrocnemius and is pennate in structure. Absent in 7-20% of limbs, the plantaris muscle inserts into the AT from its origin on the inferior aspect of the lateral femoral condyle and acts as a weak plantarflexor and knee flexor (Simpson et al., 1991).

While large variability exists regarding the point at which the triceps surae form the origin of the AT, the average length of the AT is 15 cm (range: 11 to 26 cm) (Doral et al., 2010). The width of the tendon from origin to insertion is heterogeneous, ranging from an average of 6.8 cm at the origin, 1.8 cm at the midsection, and 4 cm at the calcaneus

(Doral et al., 2010). The average anteroposterior thickness of the AT is 5.2 mm (range: 4 to 6.7 mm). Tendon thicknesses of more than 6 mm have been reported in asymptomatic subjects involved in intensive sports, suggesting a physiological adaptation to mechanical stress may occur in the AT (Kainberger et al., 1990).

The AT is encased in a paratenon, a vascularized structure that enhances the gliding ability of the tendon to enable near frictionless movement. The posterior tibial artery extends its blood supply through the anterior aspect of the paratenon, forming a passageway to the AT. How this blood supply interacts with the AT, however, is not completely understood. Microscopic observation has suggested the paratenon provides blood supply to the outermost layer of the AT with limited vascularity to the inner core of the tendon (Carr & Norris, 1989). Conversely, a study using laser Doppler flowmetry by Astrom & Westlin (1994) suggests blood flow is evenly distributed throughout the AT but varies according to age, sex, and loading conditions.

Studies have indicated asymmetric mechanical and morphological properties of the AT. In individuals who do not engage in side specific sportive activities, the AT of the dominant limb exhibits higher Young's modulus (ability of a material to withstand changes in length when under tension or compression) and greater length but a tendency toward lower maximum strain (the relative change in length of an object when an external force is applied to it) (Bohm et al., 2015). This may be a result of different loading profiles between the dominant and non-dominant limbs during daily activities. However, no differences in AT cross sectional area (CSA) were found between limbs. This finding is in agreement with a study by Ying et al. (2003) who found no difference between limbs in the mean AT thickness and AT CSA in both active and inactive young Chinese adults.

## 2.2 Acute Achilles tendon rupture

### 2.2.1 Epidemiology

The AT is the most frequently injured tendon in the lower limb. The incidence of acute AT rupture (AATR) has risen over the last few decades, likely due to primarily sedentary

adults participating in sport later into life (Schepsis, Jones, & Haas, 2002). Epidemiological reports suggest this injury occurs most frequently in middle-aged males who play recreational sports.

A Finnish study by Leppilahti et al. (1996) investigated 110 diagnosed ruptures over a 16-year period and described an increase in ruptures from two per $10^5$ inhabitants in 1979 to 1986, to 12 per $10^5$ inhabitants in 1987 to 1994. A 5.5:1 male to female ratio was observed, and 90 (82%) of cases were related to sports. In Mälmo, Sweden, Möller et al. (1996) reported 153 diagnosed ruptures between 1987 and 1991. Two thirds of the ruptures were sustained during sporting activities (mean age: 37 years) and the non-sporting injuries typically occurred in older persons (mean age: 56 years). Möller et al. also reported more ruptures in men than in women and most ruptures in women were related to non-sporting activities.

In the first North American population study to characterize incidence rates and demographics of individuals with AT ruptures, Suchak et al. (2005) reported 394 cases from January 1, 1998 to December 31, 2002, in Edmonton, Canada. In this retrospective review, a male to female ratio of 4:1 was observed and the mean age at time of rupture was 41.4 (range: 13 to 79) years. Similar to the aforementioned European studies, 75% of ruptures occurred during sporting activities and younger patients (20 to 30 years) were more likely to sustain a rupture during sports compared to older patients (50 to 60 years). More recently, Sheth et al. (2017) accessed data from provincial and national health administrative databases to evaluate the number of individuals who presented to an emergency department with an AATR in Ontario, Canada. From 2003 to 2013, a total of 27,607 patients sustained an AATR – an increase from 18 per $10^5$ persons to 29.3 per $10^5$ persons. Although the incidence of AATRs in this study is higher than previously reported, other investigations were limited to single institutions or specific cities. In addition, the study by Sheth et al. (2017) reflects a more recent time period.

Maffulli (1999) suggested that the higher frequency of ruptures in males is due to the greater prevalence of males to females who participate in sport. However, the author stated there are other unrecognized factors that contribute to this statistic. In addition,

Vosseller et al. (2013) reviewed 358 ruptures and reported sporting activities were the causative factor in 80.5% and 71.4% of men and women, respectively. This difference was not statistically different.

Bilateral ruptures are infrequent and past literature has reported a left limb dominance for AT ruptures. Hooker (1973) hypothesized that the left leg is the dominant push-off limb in those who are right handed (and vice versa). Given the higher prevalence of right-handed individuals, the left-limb dominance of AT rupture supports Hooker's hypothesis (Maffulli, 1999).

### 2.2.2 Etiology

The etiology of AATRs is multi-factorial and has not yet been fully clarified. Three main theories exist within the orthopaedic literature: pre-existing degeneration of the AT, poor vascularization of the AT, and failure at high mechanical loads. Ruptures are likely to result from a combination of the above theories, although other possibilities have been explored.

Intrinsic characteristics can place individuals at higher risk for AT pathologies, such as increasing age, male sex, obesity, and the presence of systemic diseases (Holmes & Lin, 2006). Acute ruptures have been associated with genetic/autoimmune disorders and exercise-induced hyperthermia (Dent & Graham, 1991; Dodds & Burry, 1984; Wilson & Goodship, 1994). Common extrinsic factors include physical loading of the tendon, the environment (e.g. footwear, equipment, and terrain changes), and occupation (Rees, Wilson, & Wolman, 2006). Further, certain drug therapies have been implicated as increasing AATR risk, such as corticosteroids, anabolic steroids, and fluoroquinolone antibiotics (Newnham et al., 1991; Royer, 1994).

#### 2.2.2.1 Degenerative theory

The degenerative theory suggests that pre-existing degradation of the AT can lead to a reduction in tensile strength and biomechanical weakening of the musculoskeletal unit, which can ultimately result in failure at submaximal loading conditions. While the cause

of degeneration can be unclear, metabolism of the AT is slow and tendons take approximately 100 days to form high quality collagenous scar tissue that is able to resist forces through the AT during heavy load bearing activities such as running and jumping (Paoloni, 2012). Given the arduous healing rate, there is a window during this time where individuals with pre-existing AT pathology are more susceptible to rupture. The previous literature has suggested that overstraining a tendon (either on a single or repeated occasions) can cause minor ruptures with the potential to become major if regeneration is not sufficiently completed (Barfred, 1973).

Using histology, Arner & Lindholm (1959) evaluated 74 AT specimens following rupture and found degenerative changes in all samples. Józsa and Kannus (1997) reported hypoxic degenerative tendinopathy in 45% of 397 AT rupture specimens evaluated. Tendons in this state are edematous and exhibit fragmentation and fraying of collagen fibres in the extracelluar matrix. The loss of the normal wavy alignment of collagen fibres results in a disorganized tendon structure, which may alter tension resistance.

#### 2.2.2.2 Vascular theory

Tendons require vascular support to be metabolically active, and thus compromised blood supply and its associated hypoxic environment may result in a physiologically disadvantaged state (Rees, Wilson, & Wolman, 2006). Kerkhoffs et al. (2002) hypothesized that poor vascularization alters the mechanical properties of a tendon and leads to a decrease in elasticity, which is associated with a reduced ability to resist load. Ruptures commonly occur in a hypovascular area of the AT around 2-7 cm proximal to its insertion on the calcaneus. However, Kerkhoffs' idea is commonly disputed based on the fact that there is a second zone of hypovascularity at the outermost distal area of the tendon and ruptures in this area are rare (Schmidt-Rohlfing et al., 1992). Thus, rupture site may not necessarily be correlated with poor vascularization.

#### 2.2.2.3 Mechanical theory

The mechanical theory argues that repeated loading within the normal physiological stress range of a tendon causes fatigue, eventually leading to tendon failure. While

tendons are designed to repeatedly transfer load from muscle to bone, fatigue testing protocols suggest that tendons exhibit ‘creep behaviour’. At its resting state, a tendon has a wave-like structure commonly referred to as ‘crimp’, which acts as a shock absorber (Franchi et al., 2007). At initial loading, the tendon fibres rapidly extend into a straightened position. This collagen fibre alignment is known as the ‘toe region’ and accounts for 2% of maximal tendon strain. This non-linear phase is followed by a more stable, secondary phase, in which the tendon’s length increases linearly (linear region). In the final tertiary phase, the tendon may rupture or fail (Figure 1). Strain values up to 4% of maximal load are considered physiological. Loading beyond this range (either repeated or prolonged) may result in microtrauma, which can eventually lead to failure.

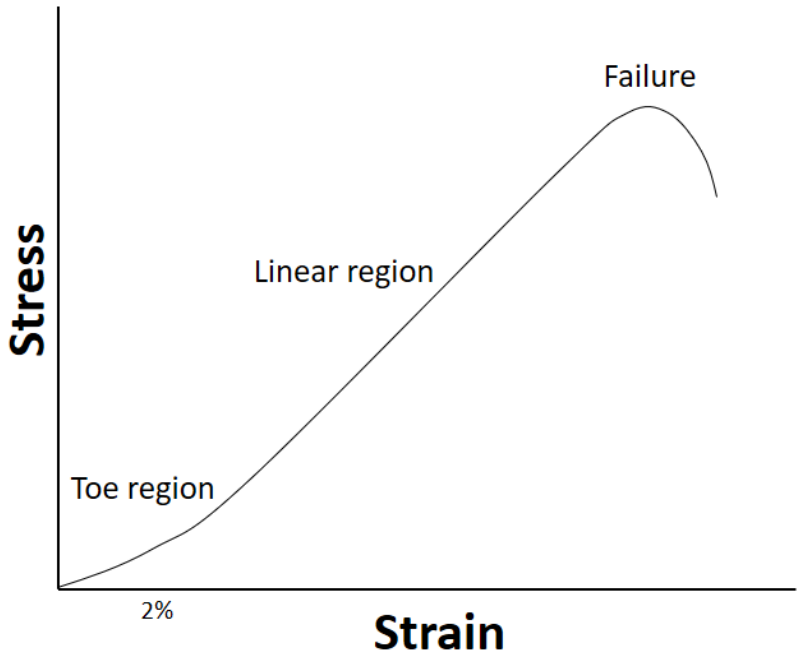


**Figure 1** Stress/strain curve of a tendon

Further, the mechanical theory postulates that a healthy AT may spontaneously rupture if select mechanical conditions are present. It has been previously stated that a healthy tendon would not rupture even when subjected to substantial loading (McMaster, 1933). However, that hypothesis is flawed in that it only takes into account the application of straight traction, a situation in which the tendon is able to distribute the strain throughout the muscle-tendon-bone complex rather than the tendon alone. It is well known that

tendons crossing joints with axes of movement at right angles to each other (such as the AT) may be exposed to oblique loads. Barfred et al. (1971) suggested that exerting an oblique force to the AT while the triceps surae are contracting might strain a small part of the tendon (10% of the fibres on the concave side) and thus induce a rupture at a submaximal force.

### 2.2.3 Mechanisms of Injury

Based on 92 AATR cases, Arner and Lindholm (1959) categorized three main mechanisms of rupture: (i) pushing off from the weight-bearing forefoot with the knee in full extension (e.g. sprint start), (ii) sudden, unexpected dorsiflexion of the ankle (e.g. slip or fall) and, (iii) violent dorsiflexion of a plantarflexed foot (e.g. falling from a height). The classic mechanism of AATRs is forced dorsiflexion as the triceps surae simultaneously contracts to move the ankle into plantarflexion. This is a common motion in repetitive jumping and sprinting sports that require rapid 'push-off' type movements, such as basketball, badminton, and volleyball. Basketball accounted for 132 of 275 ruptures (48%) in a general United States population (Raikin, Garras, & Krapchev, 2013). Over a 13-year period in Denmark, 46% of sport related AATRs were associated with badminton participation (Houshian, Tscherning, & Riegels-Nielsen, 1998). In a retrospective study of 93 consecutive patients in South-East Finland between 1986 and 1996, ruptures occurred most frequently in volleyball (Nyyssönen & Lüthje, 2000).

Further, the risk of rupture is believed to be exacerbated when there is excessive and uncoordinated muscle contractions in the lower limb. Inglis and Sculco (1981) suggested that malfunction of the inhibitory mechanism, which prevents excessive or uncoordinated muscle contractions, would cause an AATR in an otherwise 'normal' tendon. This muscle contraction asynchrony is more likely to be seen in individuals who do not follow a training schedule, which could be a reason why AATRs commonly occur in 'weekend warriors' (i.e. those who train and compete sporadically) (Egger & Berkowitz, 2017). In addition, this mechanism could also explain why athletes who return to activity after a period of inactivity are at greater risk for rupture.

## 2.2.4 Clinical presentation and diagnosis

### 2.2.4.1 Clinical presentation

An AATR typically presents as an abrupt pain in the distal posterior aspect of the individual's affected lower leg. Many patients report hearing an audible "snap" and claim they have been struck by an object or kicked in the affected area. After the incident, most individuals are unable to weight-bear or continue their activity. Swelling and bruising may be present upon physical examination. If the swelling is mild, a palpable defect can sometimes be felt along the tendon at the site of rupture.

### 2.2.4.2 Diagnosis

Ruptures of the AT are diagnosed by reviewing the mechanism of injury (patient history) and performing a physical examination. According to the *American Academy of Orthopaedic Surgeons Clinical Practice Guidelines* (American Academy of Orthopaedic Surgeons, 2009), a diagnosis can be made when two or more of the following findings are noted: a positive Thompson test, a positive Matles test, decreased plantarflexion strength, or a palpable defect proximal to insertion site (Egger & Berkowitz, 2017). Diagnosis by defect palpation should be approached with caution given that an increase in elapsed time between injury and examination is associated with a greater presence of edema and hematoma, both of which can be mistaken for an intact tendon (Leppilahti & Orava, 1998). While clinical examination is generally sufficient for diagnosis, imaging modalities can be used to confirm diagnosis, determine tear severity, or aid in preoperative planning.

#### 2.2.4.2.1 Diagnostic clinical tests

*Thompson test*

Also referred to as the 'calf-squeeze' or Simmonds test, the Thompson test is performed by squeezing the bulk of the calf muscles while the patient is in a prone position with their ankles clear over the edge of the table (Simmonds, 1957; Thompson, 1962;

Thompson & Doherty, 1962). The test is positive for an AT rupture if plantarflexion is absent or significantly decreased compared to the contralateral (i.e. uninvolved) limb (Figure 2) and negative if plantarflexion occurs when the calf is squeezed (Figure 3). The Thompson test has the highest sensitivity (0.96) and specificity (0.93) of any AT rupture diagnostic test (Maffulli, 1998).

**Figure 2** Positive Thompson test for Achilles tendon rupture

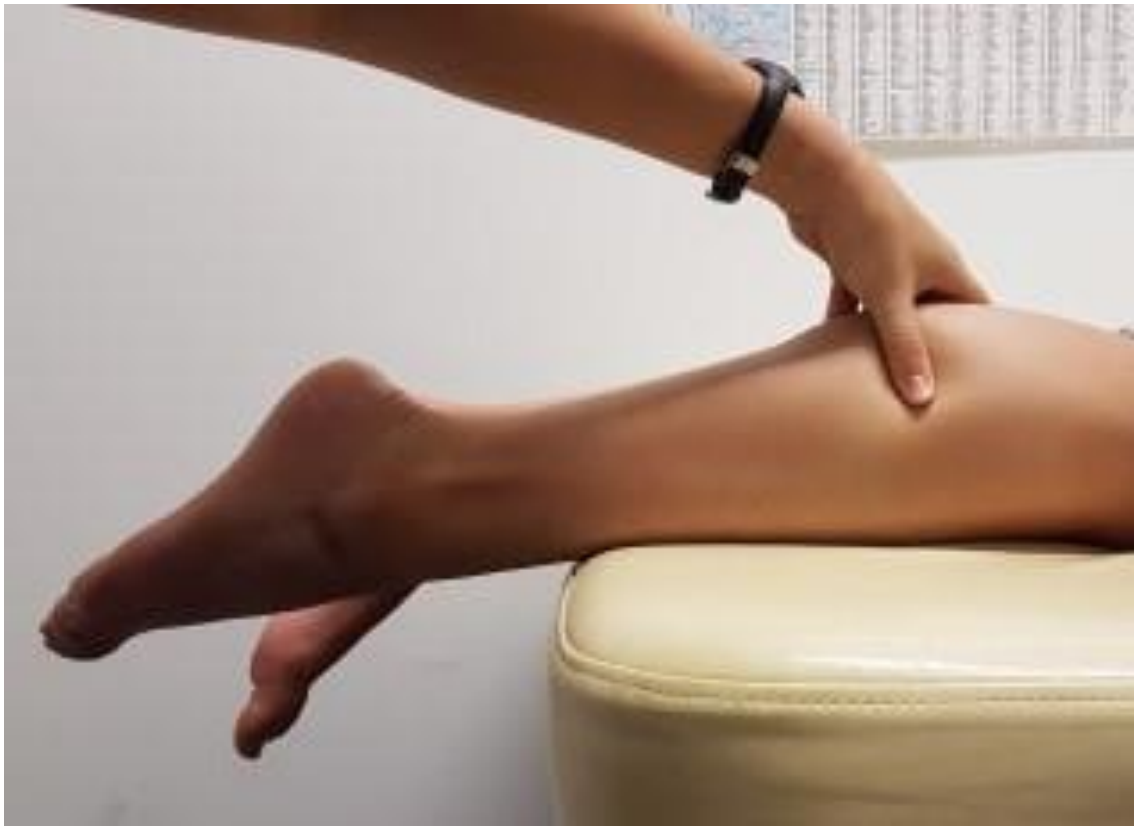

**Figure 3** Negative Thompson test for Achilles tendon rupture

*Matles test*

While lying in a prone position, patients are asked to actively flex their knees to 90º. The test is positive for a ruptured AT if the foot of the involved limb falls into a neutral or dorsiflexed (Figure 4) position compared to the uninvolved limb, which should remain in slight plantarflexion (Figure 5). Maffulli (1998) reported the sensitivity and positive predictive value to be 0.88 and 0.92 (respectively) while the patient is awake, and 0.94 and 0.97 (respectively) while patient is under anaesthesia. In the same study, the specificity of the Matles test was 0.85.

**Figure 4** Positive Matles test for Achilles tendon rupture

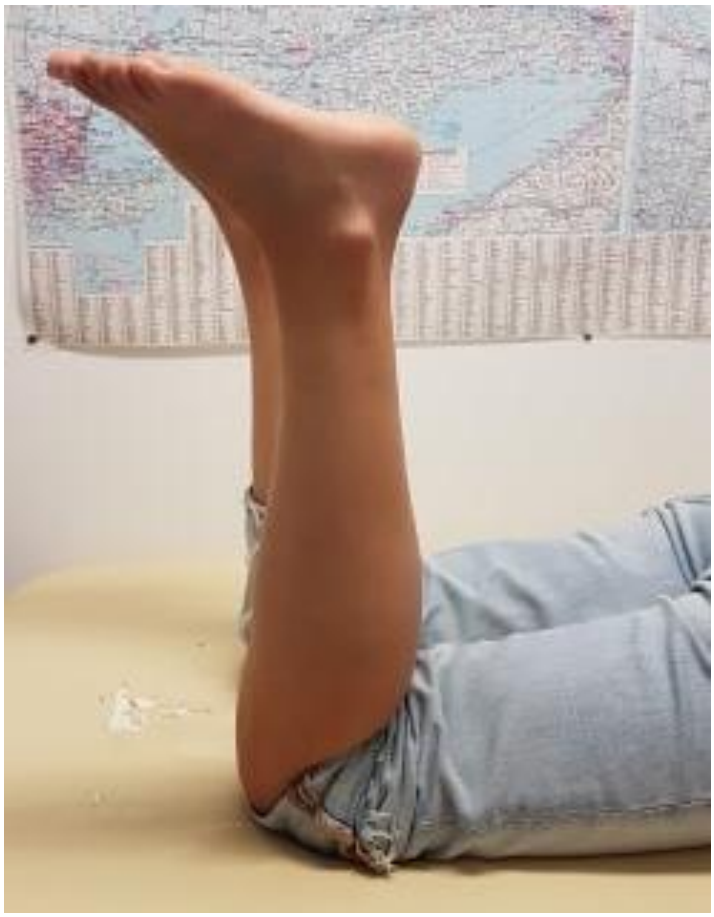

**Figure 5** Negative Matles test for Achilles tendon rupture

## 2.2.4.2.1 Diagnostic imaging

*Ultrasonography*

Ultrasonography (US) uses high frequency sound waves to create two-dimensional images of anatomical structures and has been increasingly used to investigate the integrity of the AT. It is an inexpensive, fast, repeatable, non-invasive, and non-ionizing form of medical imaging (Leppilahti & Orava, 1998). In addition, it offers the opportunity to conduct real-time, dynamic (i.e. during plantar- and dorsiflexion movements) examination in more than one plane, which can aid in detecting tendon discontinuity (Leppilahti & Orava, 1998).

The AT can be examined with ease using US given its superficial location and regular shape (Kallinen & Suominen, 1994). A normal AT will appear as an echogenic pattern of parallel fibrillary lines in the longitudinal plane and as an echogenic round-to-ovoid shape (4 to 6 mm anterior to posterior diameter) in the transverse plane (Bleakney, White, & Maffulli, 2005). Increased tendon thickness is typically associated with tendinopathies, and focal hypoechoic areas within the AT are indicative of tendinopathic lesions. Following AT rupture, a hematoma at the tear site may be visible on US and, although varied, an acute hematoma is usually echogenic in appearance (Hollenberg, Adams, & Weinberg, 1998). While it can be difficult to distinguish a torn tendon end from a hematoma, colour Doppler sonography can be used to differentiate between structures (hematoma will not demonstrate colour flow) and to determine whether tendon ends are apposed or separated (Hollenberg, Adams, & Weinberg, 1998). Although US has been reported to be highly accurate in diagnosing fully ruptured ATs, this imaging modality is not wholly reliable for distinguishing partial from complete tears and requires an experienced radiologist (Hartegerink et al., 2001; Kayser, Mahlfeld, & Heyde, 2005; Paavola et al., 1998).

*Magnetic resonance imaging*

Commonly used to provide definitive diagnoses of a variety of musculoskeletal conditions, magnetic resonance imaging (MRI) scanners use strong magnetic fields to excite protons in tissues containing water in order to create a signal that can be processed to form images of the body. Advantages of this powerful imaging modality include superior soft tissue contrast, non-invasive and non-ionizing protocols, and the ability to produce multiplanar images (Marcus, Reicher, & Kellerhouse, 1989; Mink, Deutch, & Kerr, 1991). Consequently, MRI can provide extensive information on the internal morphology of the tendon and surrounding structures. Despite the superior quality of images produced, its use for AT rupture diagnostic purposes is limited due to its high cost and the sufficient diagnostic accuracy of a focused history and physical examination. However, it remains a valuable tool for evaluating the morphology of the tendon and surrounding tissues during the healing process following AT rupture.

A healthy AT presents as a dark area of low signal intensity on all imaging sequences due to its low water content and compact arrangement of collagen fibres (Bleakney, White, & Maffuli, 2005). On sagittal images, the normal average thickness of the AT has been reported to be approximately 6 mm, and the anterior and posterior margins should be parallel below the soleus insertion (Schweitzer & Karasick, 2000). On axial slices, the anterior aspect of the AT should appear concave for most of its course.

A number of sequences can be used to locate abnormalities in the AT (Bleakney, White, & Maffuli, 2005). A T1-weighted sequence (longitudinal relaxation time, or time taken for protons to realign with the external magnetic field) (Figure 6) can be used to provide precise anatomic delineation of the AT. Increased fluid is associated with many tendon pathologies, and can be easily detected with a T2-weighted sequence (transverse relaxation time, or time taken for spinning protons to lose phase coherence among the nuclei spinning perpendicular to the main field) (Figure 7). Further, inversion recovery and fat saturated T2-weighted sequences can show greater signal contrast between free water and the fat surrounding the tendon. Full ruptures of the AT present as a complete disruption of the tendon fibres and high signal intensity at the site of rupture on T2-weighted images (Keene et al., 1989).

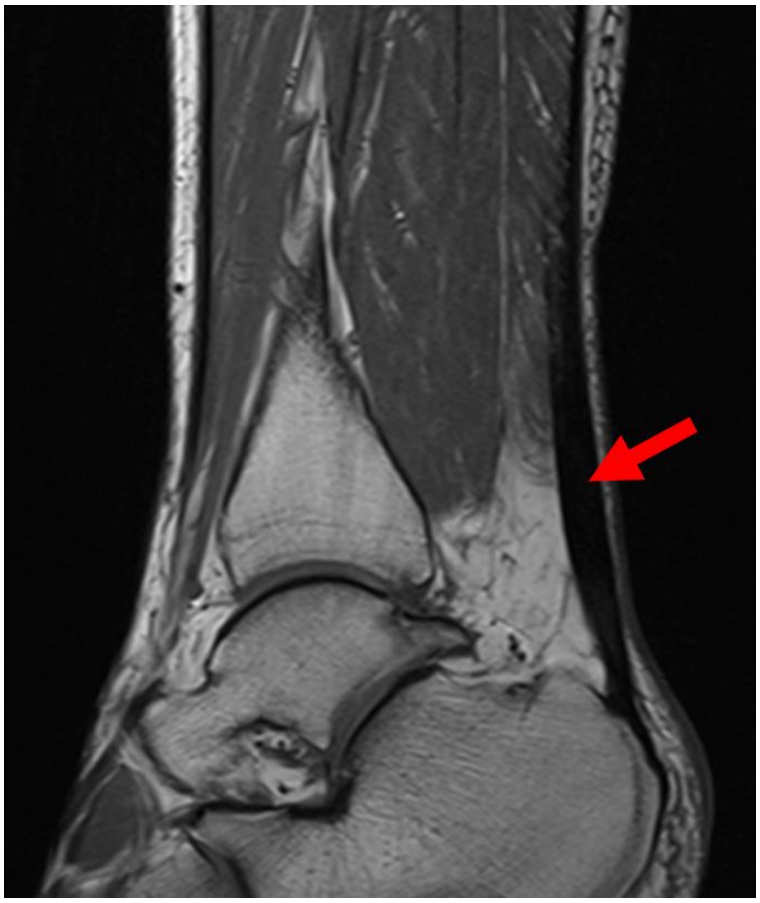

**Figure 6** Sagittal T1-weighted turbo spin echo magnetic resonance image of the Achilles tendon (red arrow)

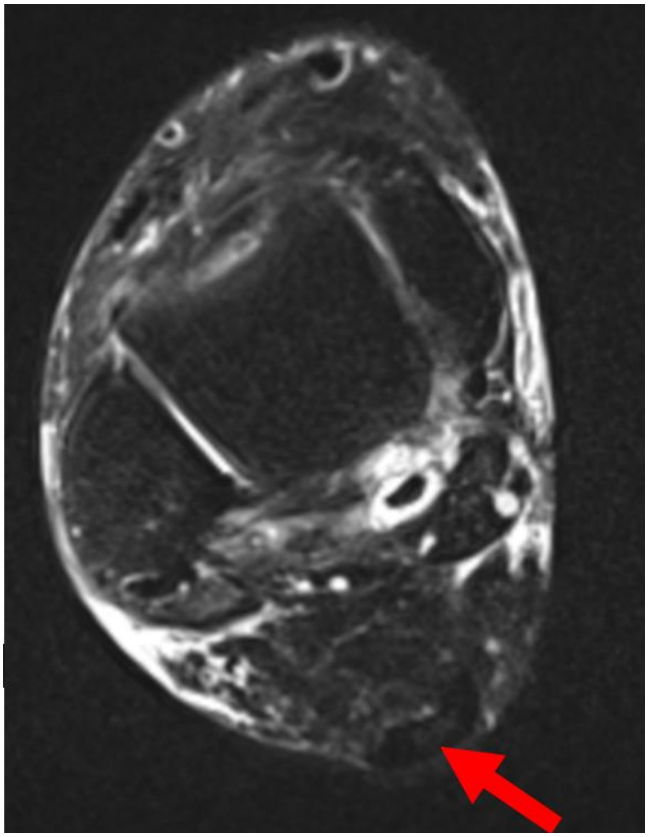

**Figure 7** Axial T2-weighted turbo spin echo fat saturated magnetic resonance image of the Achilles tendon (red arrow)

MRI has also been used to assess healing in the AT post-rupture. Fujikawa et al. (2007) evaluated MR images of the AT at approximately 4, 8, and 12 weeks post-surgical repair. In the first session, a persistent gap in all 40 tendons evaluated was identified on T1-weighted images. Conversely, T2-weighted images indicated a gap in only 32 (82%) of the tendons. In the second MRI session, T1 and T2-weighted images showed gaps in 25 (62.5%) and 19 (47.5%) of the tendons, respectively. By the third session, neither T1 nor T2-weighted images indicated a tendon gap. Interestingly, palpation of the AT revealed no gap at both the second or third sessions despite gaps appearing on MRI. The authors explained this discrepancy by suggesting that, at this stage in healing, the gap may have been filled with granulation tissue, but mature fibrous tissue may have not be present. While imaging would be able to differentiate between tendon and granulation tissue, the

defect may not have been appreciated on palpation. For this reason, the authors cautioned clinicians against using palpation alone as a reference standard for assessing tendon fusion.

A study by Karjalainen et al. (1997) consecutively recruited 20 patients with 21 surgically repaired AT ruptures to undergo MR imaging, clinical examination, and functional testing at 3 and 6 weeks, and 3 and 6 months post-surgery. The average CSA of the affected AT was enlarged at all time points, reaching a maximum of 6.1 times that of the contralateral tendon at three months post-surgery. T-2 weighted images showed variable-sized areas of atypical high-intensity signal in the AT during the early rehabilitation period (less than three months) in all but two patients. By six months, these areas had either greatly reduced in size or disappeared. While patients with smaller intratendinous lesions had normal recoveries, the three patients with the largest lesions (more than 50% of the tendon) had clinically poorer outcomes at three months. Further, five patients with abnormal gait patterns at three months had significantly larger lesions than those who exhibited normal gait. It was concluded that MRI is a valuable tool by which to assess the internal structures of surgically repaired ATs. The authors acknowledged that the long-term healing process of the AT is unknown, and should be investigated using imaging modalities. Additionally, it was advised that MRI measures should be correlated with clinical and functional findings.

## 2.3 Treatment of Achilles tendon rupture

Treatment options for an AT rupture can be broadly classified into two categories: operative (open or percutaneous techniques) or non-operative (cast immobilization or functional bracing). Past studies have suggested that surgical intervention carries a higher risk of infection, wound complications, and nerve injury (Carmont et al., 2011; Khan et al., 2005). On the other hand, some studies report that conservative treatment is associated with higher re-rupture rates. While surgery was once the preferred treatment and considered the gold standard for AATR repair, a number of high quality randomized controlled trials and subsequent systematic reviews have suggested there is no difference between patients treated surgically and non-surgically (Nilsson-Helander et al., 2010;

Ochen et al., 2018; Willits et al., 2010). The tendency towards surgery has especially been challenged since the introduction of early range of motion protocols (i.e. acceleration functional rehabilitation) in non-operative management, which have yielded superior results compared with traditional prolonged immobilization protocols (Soroceanu et al., 2012). These promising results have encouraged a shift from surgical intervention towards conservative treatment over the last few decades (Ganestam et al. 2016; Huttunen et al. 2014; Mattila et al. 2015; Sheth et al., 2017). As controversy persists as to which treatment is superior, decisions can be made based on the patient's age, health, and athleticism, the time to diagnosis, as well as the preferences of the surgeon and patient (Lim, Dalal & Wassem, 2001). Debate is likely to continue until the publication of larger randomized controlled trials that stratify by age and athletic level (Miller & Chiodo, 2017).

## 2.3.1 Operative

Bradley and Tibone (1990) stressed the importance of choosing the most appropriate surgical technique for each patient to minimize complications and enhance recovery. Conventionally, operative repair is chosen for athletes, young patients, and those who have experienced a delayed diagnosis (Lim, Dalai & Waseem, 2001). Advocates for surgery cite lower re-rupture rates compared to conservative management and contend that the normal tension and length of the AT can only be achieved through surgical intervention (Brown, Fu, & Hanley, 1981; Lee & Schuberth, 2012).

### 2.3.1.1 Open repair

Open repair involves a single large incision at the site of rupture, allowing for abutment of the tendon ends and a clear assessment of tendon length. The procedure is thought to result in better ankle range of motion and less residual tendon lengthening and triceps surae atrophy. It is believed that these advantages could lead to higher rates of returning to sport at the pre-injury level (Cetti et al., 1993). Despite these advantages, open repair carries an increased risk of skin-tendon adhesions, superficial and deep infection, delayed healing of the surgical wound, sural nerve lesions, and suture granulomas (Gigante et al.,

2008). Further, severe complications, such as deep vein thrombosis, pulmonary embolism, and death have been reported (Gigante et al., 2008). Care must be taken to protect the sural nerve and saphenous vein, and surgeons should attempt to preserve major blood vessels to the tendon (Bradley & Tibone, 1990). Bradley and Tibone (1990) suggest that open surgery should only be considered in patients with optimal skin conditions and that surgery should be delayed until edema subsides.

#### 2.3.1.2 Percutaneous

In this surgical procedure, sutures to re-appose the AT are passed through small stab incisions on either side of the tendon. The percutaneous technique was first described by Ma and Griffith (1977) as a solution to decrease the high wound complication rate of open repairs and to enhance cosmetic results of surgery. While this technique does not allow the surgeon to view the rupture directly, ultrasound and endoscopy can be used for visualization purposes (Carmont et al., 2011). Those who are older, less active, and individuals who wish to avoid large scars generally opt for percutaneous surgery.

Similar to open repair, surgeons must be cautious to avoid damaging the sural nerve and saphenous vein. This risk can be minimized by reviewing the neurovascular anatomy of the region and practicing proper placement of the stab wound. Further, novel percutaneous techniques have been developed to minimize the risk of iatrogenic injury to the sural nerve (Zappia et al., 2018). However, a study by Bradley and Tibone (1990) warned that when compared to patients treated with open surgical repair, those treated with percutaneous repair can be vulnerable when the cast is removed at two months.

### 2.3.2 Non-operative

To treat an AT conservatively, the ankle is first immobilized in plantarflexion in order to re-approximate the tendon ends, which allows for the AT and surrounding tissues to undergo biological repair (Gigante et al., 2007). After the initial immobilization period, protocols can differ with respect to controlled mobilization and weight-bearing. Traditional non-operative rehabilitation protocols for AT ruptures involved wearing a rigid, non-weight-bearing cast for approximately 6 weeks post-injury. Over the past

decade, rehabilitation has shifted from prolonged immobilization towards accelerated functional rehabilitation protocols. Bradley and Tibone (1990) encouraged conservative management for sedentary older patients and those who are chronically ill or debilitated. The avoidance of hospitalization also reduces costs associated with post-injury care (Gigante et al., 2008).

### 2.3.2.1 Accelerated functional rehabilitation

While accelerated functional rehabilitation protocols vary considerably and often lack standardization, they typically begin with functional bracing of the ankle in the equinus (restricted dorsiflexion) position (Figure 8). A functional brace allows for early controlled motion through the ankle joint, and patients can be immediately progressed to weight-bearing as tolerated following rupture.

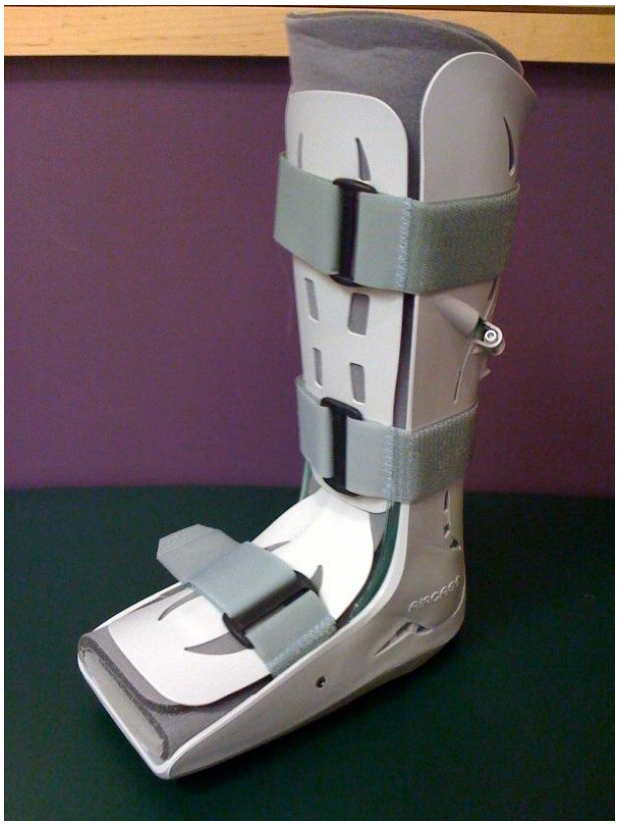

**Figure 8** An example of a functional brace. A heel lift can be placed inside

A systematic review of overlapping meta-analyses by Zhao et al. (2017) found that, when compared to immobilization protocols, early rehabilitation protocols result in higher patient satisfaction, earlier return to function, and similar complication rates. Several physiological and biomechanical hypotheses have been suggested to explain the superior results of accelerated protocols. Throughout the phases of tendon healing (inflammation, proliferation, and remodelling), the tensile strength of the AT increases as new scar tissue is formed. During the early phases of healing, the new tissue is biomechanically inferior, resulting in increased stiffness (Evans & Stanish, 2000). Engaging in active and passive ankle joint range of motion can reduce joint stiffness and local swelling and decrease atrophy of the calf musculature (Zhou et al., 2017). Animal studies have demonstrated that early movement through the tendon can decrease excessive adhesion formation, improve the biomechanical properties of scar tissue, and enhance the gliding properties of the tendon (Enwemeka, 1992; Lin, Cardenas, & Soslowsky, 2004).

### 2.3.3 Operative vs non-operative

Early systematic reviews and meta-analyses suggested that compared to conservative treatment, surgical repair can reduce the risk of re-rupture, but increase the probability of complications. Jiang et al. (2012) conducted a meta-analysis to investigate the clinical effectiveness of operative compared to non-operative treatment in acute AT rupture patients. Results from 10 randomized controlled trials (894 patients) showed that operative was superior to non-operative treatment as it resulted in lower risk of re-rupture (relative risk (RR) 0.44, 95% confidence interval (CI) (0.26-0.74), p=0.002) and faster return to work (mean difference (MD) = 23.75, 95% CI (-41.61-5.89), p=0.009). Conversely, surgical repair was inferior to conservative management regarding complication risks (RR 4.07, 95% CI (1.56-10.67), p=0.004), though specific complications were not explicitly stated. There were no differences between groups in the number of patients who resumed pre-injury sports. The authors were unable to conduct a meta-analysis on functional outcomes because of difficulty extracting and pooling data due to different assessment systems used in the included studies. The authors concluded that an operation could lead to a faster recovery time; however, disagreements persist regarding specific functional outcomes.

Similarly, Wilkins and Bisson (2012) reviewed seven level I trials (677 patients) and found that open repair was associated with a significantly lower re-rupture rate compared with non-operative treatment (3.6% vs 8.8%). Surgical treatment resulted in a higher incidence of deep infections (2.36% surgical vs 0% non-surgical, p=0.0113), non-cosmetic scar complaints (13.1% surgical vs 0.62% non-surgical, p<0.001), and sural nerve sensory disturbances (8.76% surgical vs 0.78% non-surgical, p<0.001). However, the pooled rate of deep vein thrombosis was not significantly different between groups (7.08% surgical vs 10.24% non-surgical, p=0.1796). This group was also unable to compare the return of strength in the involved lower limb and suggested future studies should attempt to standardize strength testing in a more functional and reproducible manner.

Following randomized controlled trials that introduced early functional rehabilitation protocols, subsequent systematic reviews have suggested updated recommendations. Zhou et al. (2018) performed a meta-analysis to (1) compare operative and non-operative treatment for AT ruptures, and (2) evaluate if the re-rupture rate in studies that included early functional rehabilitation protocols differed from those that did not. Ten randomized clinical trials (934 patients) were included. While those managed conservatively had a comparatively higher re-rupture rate than those treated with surgery (RR 0.38, 95% CI (0.23-0.63), p=0.0002), this rate was equivalent in both groups if early range of motion exercises were performed. Subgroup analysis showed that the operative group displayed significantly higher rates of deep infection (RR 4.18, 95% CI (1.20-14.53), p=0.02), adhesions (RR 10.24, 95% CI (4.03-26.03), p<0.00001), and sural nerve injury (RR 7.94, 95% CI (1.93-32.71), p=0.004). However, there were no differences between groups regarding deep vein thrombosis (RR 0.42, 95% CI (0.12-1.42), p=0.16) and superficial infection (RR 1.13, 95% CI (0.58-2.19), p=0.72). This study was the first to conduct a meta-analysis to evaluate functional outcomes. The surgical group demonstrated superior results in two different jumping tasks (drop countermovement jump, MD = 7.30, 95% CI (2.71-11.9), p=0.002); hopping, MD = 12.86, 95% CI (4.05-21.67), p=0.004); and one muscular endurance test (heel rise work, MD = 7.36, 95% CI (1.51-13.20), p=0.01) at 12 months post-injury. There were no differences between groups in two strength tests (concentric power, MD = 7.23, 95% CI (-2.59-17.06), p=0.15; eccentric power, MD =

5.67, 95% CI (-1.46-12.79), p=0.12) and one muscular endurance test (heel-rise height, MD = 2.76, 95% CI (-1.45-6.97), p=0.2). Finally, no difference between groups was observed regarding the proportion of patients who returned to previous levels of sport (RR 1.04, 95% CI (0.65-1.67), p=0.87). The authors advised that conservative treatment is a viable option if the hospital at which the patient is treated offers a functional rehabilitation program that features early range of motion.

Deng et al. (2017) also included functional outcomes in their systematic review and meta-analysis to compare the clinical outcomes of surgical versus conservative management for AT rupture. Pooled results from eight randomized controlled trials (762 patients) showed that re-rupture rate was significantly lower in the surgical compared to the non-surgical group (RR 0.38, 95% CI (0.21-0.68), p=0.001). There were no significant differences between groups in the incidence of deep vein thrombosis (RR 0.40, 95% CI (0.13-1.26), p=0.12), return to sport (RR 1.06, 95% CI (0.90-1.24), p=0.50), plantarflexion (MD = -0.11, 95% CI (-4.52-4.31), p=0.96) and dorsiflexion (MD = 0.80, 9% CI (-1.87-3.47), p=0.56) range of motion, Achilles Tendon Total Rupture (MD = 2.00, 95% CI (-3.49-7.49), p=0.47), and Physical Activity Score (MD = -0.05, 95% CI (-0.37-0.27), p=0.77). Based on the re-rupture rate, surgery was recommended. However, the authors did not consider the effects of different conservative management protocols, and suggested that longer-term follow-up data are needed to provide higher levels of evidence to guide clinical practice.

Most recently, Ochen et al. (2018) included both randomized controlled trials (10 studies, 944 patients) and observational studies (16 retrospective and 3 prospective studies, 14,918 patients) in a systematic review and meta-analysis to evaluate outcomes following AT rupture. The overall pooled effect from the 29 studies showed that operative treatment was associated with significantly fewer re-ruptures than non-operative treatment (RR 0.43, 95% CI (0.31-0.60), p<0.001). In randomized controlled trials, re-ruptures occurred in 2.3% of operatively treated patients compared with 3.9% of conservatively managed patients. Conversely, results showed a significant reduction in re-rupture rate after operative treatment when compared with non-operative treatment in studies that incorporated an early (4 weeks or less) weight bearing protocol. The overall

pooled effect of accelerated functional rehabilitation with early weight bearing showed no significant differences in re-rupture rate between operative and non-operative treatment. The incidence of complications was significantly higher in the surgical cohort (RR = 2.76, 95% CI (1.84-4.13), $p<0.001$), and the main complications were infection and deep vein thrombosis in operative and non-operative patients, respectively. The authors were unable to pool functional outcome or return to work/sport data due to large variations and lack of quantitative data in the studies included. In their conclusion, the authors noted that while operative treatment is associated with a lower risk of re-rupture in most studies, the re-rupture rate in this population is low and differences between treatments are small (risk difference = 1.6%). They advised that treatment decisions should be based on patient specific factors and shared decision-making.

## 2.4 Long-term outcomes of acute Achilles tendon rupture

The aforementioned studies comparing operative and non-operative interventions focused on evaluating AT patients in the short term (under 3 years). In many of these studies, patients continued to exhibit side-to-side deficits at the final follow-up, and not all patients return to pre-injury level of sport following rupture. Given the lingering controversy in selecting the optimal treatment and the uncertainty of the healing process of the AT, long-term studies are warranted.

Hufner et al. (2006) investigated the long-term (mean: 5.5 years; range: 2 to 12.7 years) effects of a functional non-operative protocol in 125 AT rupture patients (105 male; mean age at rupture: 39.8 years (range: 19.9 to 69.8)). The treatment protocol involved wearing a cast for 1 to 3 days post-rupture, followed by 8 weeks in a boot with a 3 cm heel lift. Patients were permitted to discontinue boot use after 8 weeks if sonographic evaluation indicated a healed tendon. It was reported that 10.4% of patients experienced complications, including re-rupture (6.4%), deep vein thrombosis (2.4%), and soft-tissue abnormalities due to the boot (1.6%). At the final follow-up, 96% of the patients were pain free, though ultrasound examination did not reveal any pathologic findings in the five patients who were experiencing pain. Measured at a distance of 15 cm below the medial knee joint line, the calf circumference in the involved limb was on average 2.1

(range: 0 to 3) cm smaller than the uninvolved. Compared to the contralateral limb, active plantarflexion and 1-minute tiptoeing was normal in 82 (65.6%) and reduced in 43 (34.4%) of patients. While it was reported that the involved AT was lengthened (indicated by increased passive dorsiflexion compared to contralateral side) in 21 (17%) of patients, the authors divulged that 12 of those patients were noncompliant with the treatment protocol (i.e. did not wear the boot continuously after 4 weeks). Ultrasound imaging revealed that the diameter of the involved tendon was significantly larger than the uninvolved (mean: 9.5; range 6.8 to 13.5 mm). Authors concluded that while functional non-operative treatment allows for early full weight-bearing and may contribute to lower re-rupture rates compared to studies with cast immobilization, patients must wear the boot continuously until 8 weeks post-rupture to acquire the benefits.

Krueger-Franke, Siebert, and Scherzer (1995) evaluated 122 (107 male, mean age: 41 years (range: 22 to 74) operatively treated patients at an average of 5.9 (range: 2.2 to 12.3) years post-rupture. Post-surgery, the involved limb was first immobilized for two weeks in 30° plantarflexion, followed by 15° of plantarflexion for the subsequent two weeks, followed by the neutral position in a short-leg walking cast for the final two weeks. The authors stated that physiotherapy was only necessary in isolated cases. Normal scar tissue, palpatory examination of the AT, one-legged toe raises, and range of motion was reported in 117 (96%), 105 (86%), 109 (89%), and 101 (83%) patients, respectively. Calf circumference measured at a distance of 15 cm distal to the medial knee joint was on average 1.4 cm smaller on the operated compared to the contralateral limb. Plantarflexion isokinetic strength testing revealed the involved limb was weaker than the uninvolved limb by 6.3 Nm (range: 46.8-57.3 Nm) and 6.9 Nm (range: 14.2-38.0 Nm) at 30°/s and 120°/s, respectively. Although US examination showed full continuity of the AT in all patients, the affected tendon remained thickened in 64 individuals.

In a multi-centre retrospective study, Rosso et al. (2013) assessed 52 AT rupture patients (mean age: 48.6±8.7 years) at an average of 91±31.3 months post-rupture. The cohort consisted of patients who had undergone one of three treatments: open reconstruction (n=21); percutaneous/mini-invasive (n=16), or; conservative (n=15). An early functional

rehabilitation protocol was prescribed to all patients and was identical across study centres. Following surgery or diagnosis (conservative), patients were fitted into a stability boot. They were permitted to partially weight-bear for 2 weeks in 20° plantarflexion and fully weight-bear in 20° of plantarflexion during weeks 3 and 4. Finally, plantarflexion was reduced to 10° at week 5 and 6. In general, scores on the Short Form-36, Achilles Tendon Total Rupture Score, American Orthopaedic Foot and Ankle Score, and Hannover questionnaires were 'good' to 'excellent' with few outliers. Scores were not significantly different between groups. Maximal calf circumference was statistically different between the affected and healthy limb in the total pooled sample (37.9 affected vs 39.2 cm healthy, $p<0.0001$) but was not different between treatment groups. Muscle volume of the soleus and gastrocnemius was quantified using MRI and was an average of 17% smaller in the involved limb compared to the uninvolved for all groups. MRI was also used to measure mean AT length, which was significantly longer in the affected compared to the healthy leg (198.4±24.1 mm vs 180.6±25 mm, $p<0.0001$) but not significantly different between treatment groups. Finally, fatty infiltration of the calf musculature did not differ between treatment groups. However, fatty atrophy was still present after more than 7.5 years of follow-up. Given the lack of significant differences in outcomes between groups, the authors were unable to give general recommendations regarding the best treatment option for AT rupture patients.

In another paper examining the same cohort of patients, Rosso et al. (2015) evaluated long-term biomechanical outcomes following AT rupture. Measured on an isokinetic dynamometer at 30°/s, peak plantarflexion torque in the affected limb was reported to be on average 13% lower than the unaffected (80.4±29.7 vs 92.1±27.4 Nm). No differences between treatment groups. The mean total 'push-off force' (POFF) was calculated while walking on an instrumented treadmill. No differences between the involved and uninvolved limbs, or treatment groups. However, when the open and percutaneous participants were grouped into a 'surgical' cohort and compared to those treated non-operatively, the surgical cohort exhibited a higher relative POFF per body weight in the affected limb. No definitive recommendations regarding optimal treatment were given; however, the authors stated that no matter which treatment was chosen, loss of function is commonly seen after AT rupture and can persist at more than 7.5 years post-injury.

Brorsson et al. (2017) sought to evaluate calf muscle performance and patient-reported outcome scores beyond five years post AT rupture. Since patients were recruited from a previous trial that had randomized patients to either receive surgical (n=34) or non-surgical treatment (n=32), comparisons could be made between the one year, two year, and long-term (average time since rupture: 7±1 years) follow-ups. In the involved limb, there was a significant main effect of time for maximal heel-rise height, maximum number of consecutive heel-rises, and heel-rise work. However, there was no improvement in calf muscle endurance from the two to seven year follow-up, except in maximal heel-rise height. There were no statistically significant differences in calf muscle performance or patient-reported outcomes between either treatment groups, except the difference between limbs for heel-rise repetitions was smaller in the surgical cohort. Results suggest that significant deficits in calf muscle endurance and strength persist seven years post AT rupture, regardless of treatment.

## 2.5 Operative versus non-operative treatment of acute Achilles tendon rupture, Willits et al. (2010)

In a study published in 2010, Willits et al. evaluated individuals who ruptured their AT between 2000 and 2007. Patients were investigated at two sites in Canada (Fowler Kennedy Sport Medicine Clinic, London and the University of Calgary Sport Medicine Centre, Calgary) and randomized to receive either open operative repair (n=72) or non-operative (n=72) treatment. All patients followed the same accelerated functional rehabilitation protocol that featured early weight-bearing and range of motion (Appendix A). The primary outcome was re-rupture rate, based on the diagnosis of a positive Thompson test, the presence of a palpable gap, and loss of plantarflexion strength. Secondary outcomes included: isokinetic strength (30°/s, 60°/s and 240°/s) measured on a dynamometer; the Leppilahti score; active ankle range of motion; and calf circumference measured at 15 cm distal to the inferior pole of the patella.

Two and three re-ruptures were sustained in the operative and non-operative groups, respectively. All re-ruptures occurred within one to three months post initial injury. These rates are similar to other studies featuring early mobilization rehabilitation protocols, but

different to those which involved prolonged immobilization. More complications occurred in the operative (11; deep vein thrombosis, AT tethered to skin, hypertrophic scar, superficial infection, deep infection, pulmonary embolus, and wound complications) compared to the non-operative group (three; deep vein thrombosis, substantial pain, and failure to heal). At the one-year follow-up, the affected limb was able to achieve at least 80% of the plantarflexion and 100% of the dorsiflexion strength of the unaffected limb at all 3 isokinetic velocities. The plantarflexion strength ratio (affected to non-affected limb) at 240°/s was slightly higher in the operative group and this difference was significant (MD = 20.25%, 95% CI (0.07-40.4%), p=0.05). No significant changes in strength from one to two years was observed in either group or test velocity. The small but significant difference in plantarflexion strength in favour of the operative group at 240°/s was maintained at the two year follow-up (MD = 14.15%, 95% CI (1.12-27.19%), p=0.03). The side-to-side difference in active plantarflexion range of motion was higher in the non-operative compared to the operative group. No other statistically significant differences were found at either time points.

While plantarflexion strength testing favoured the operative group at both time points at one speed, the authors acknowledged that the difference was small and the clinical importance of isokinetic testing is uncertain given the lack of standardization among protocols. Due to the higher rate of complications and no clinically important differences between groups, the authors supported the use of accelerated functional rehabilitation and non-operative care for acute AT ruptures.

# Chapter 3

# 3 Objectives and Hypotheses

Long-term deficits after AATR in the involved limb are unknown. Further, while there has been a shift toward non-operative care for patients with AT ruptures, surgery is still frequently performed. Short-term studies have suggested there is no benefit of operative repair over non-operative care; however, we lack information regarding the long-term comparisons of treatment options. Finally, it is uncertain how the involved and uninvolved limbs change over time post-AATR.

## 3.1 Primary objective and hypothesis

Objective: To compare involved and uninvolved limbs ≥10 years after treatment for AATR.

Hypothesis: Deficits will be identified in the involved compared to uninvolved limb.

## 3.2 Secondary objective and hypothesis

Objective: To describe changes in the involved limb and side-to-side differences from the 2-year to final follow-up, and compare between treatment groups.

Hypothesis: Side-to-side differences will remain present at the final follow-up, though both limbs will deteriorate over time with no difference between treatment groups.

## 3.3 Tertiary objective and hypothesis

Objective: To compare patients treated operatively and non-operatively.

Hypothesis: There will be no differences between treatment groups.

# Chapter 4

# 4 Methods

## 4.1 Study design

We completed a single-centre long-term follow-up of a previous multi-centre randomized controlled trial comparing outcomes of patients with AATR treated with operative repair and accelerated functional rehabilitation versus accelerated functional rehabilitation alone (Willits et al., 2010). We attempted to contact all patients from the Fowler Kennedy Sport Medicine Clinic who were participants in the initial study (n=80). They were asked to attend a one-time visit to testing facilities (Wolf Orthopaedic Biomechanics Laboratory and Centre for Functional and Metabolic Mapping, Robarts Research Institute) on Western University campus. Outcomes assessors were blind to group allocation. This was achieved by a volunteer uninvolved in the study placing a piece of opaque tape over tendon where the surgical scar was (operative patients) or would be (non-operative patients). The tape did not interfere with any of the testing procedures. This follow-up study was approved by the Research Ethics Board at Western University (Appendix B).

## 4.2 Eligibility criteria

All participants from the previous trial (Willits et al. 2010) were eligible. Inclusion criteria for the initial trial were: complete primary AATR demonstrated by a positive Thompson squeeze test and the presence of a palpable gap; presenting within 14 days after injury; between 18 and 70 years of age; willing and able to comply and carry out the prescribed rehabilitation protocol; able to provide informed consent; and able to speak English. Exclusion criteria included: ipsilateral injury; open injury; fluoroquinolone-associated rupture (i.e. rupture 2 weeks after taking this medication); AT avulsion from the calcaneus; and surgical contraindications. Those who were ineligible to undergo MRI due to incompatible hardware inside their bodies were still invited to participate in the study and complete the other tests.

## 4.3 Interventions

Regardless of treatment allocation, all participants followed an identical accelerated functional rehabilitation program (Appendix A). Participants were permitted to use modalities to reduce pain and swelling throughout the program.

*Operative treatment*

Two non-absorbable sutures were placed across the AT tear in a Krackow-type stitch pattern (Figure 9). Additional absorbable sutures were placed at the tear site to re-appose any remaining tendon ends, as well as along the paratenon. During the procedure, the ankle was placed in plantarflexion to appose the tear ends and the contralateral limb was used as a guide for tendon length. Finally, a posterior back slab splint was applied to secure the ankle in 20° plantarflexion (optimal position for healing). At 2 weeks post-intervention, the slab was removed and the accelerated functional rehabilitation program commenced.

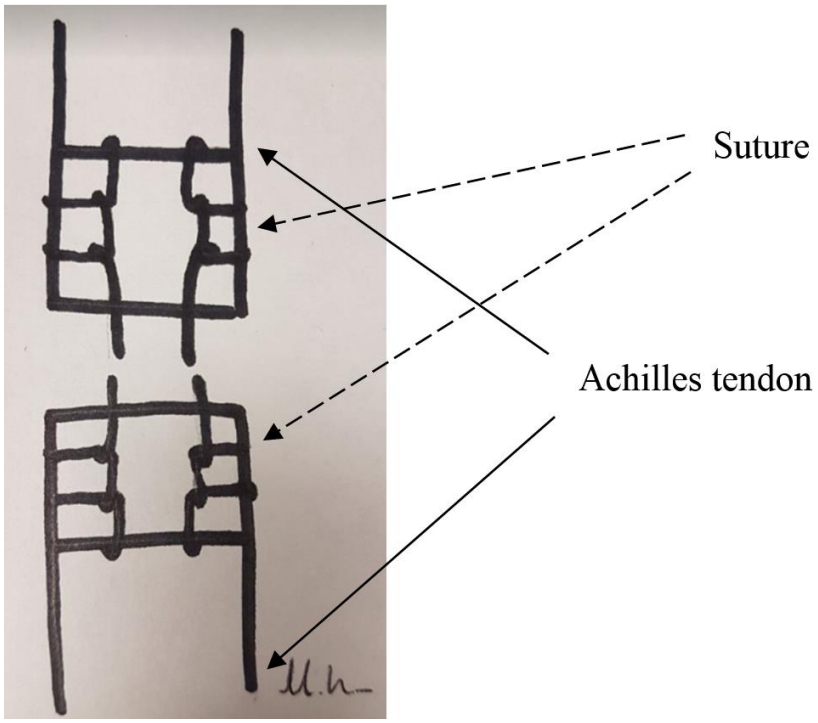


**Figure 9** An illustration showing the surgical Krackow-type suture pattern (dashed arrows) in the proximal and distal Achilles tendon stumps (solid arrows)

## 4.4 Outcome measures

We grouped our outcome measures into four categories (magnetic resonance imaging (MRI), physical examination, performance-based, and patient-reported). All MRI, performance based, and clinical outcomes were measured bilaterally, beginning with the uninvolved limb.

### 4.4.1 MRI outcome measures

Participants underwent bilateral 3-Tesla magnetic resonance imaging (MAGNETOM Prisma, Siemens) at the Centre for Functional and Metabolic Mapping, Robarts Research Institute, Western University. Participants lay supine on the table and then entered the bore of the magnet feet first. All images were evaluated by the same experienced musculoskeletal radiologist (AS) and a trained assessor (MK). Images of the AT were obtained in the sagittal and axial planes, while images of the calf musculature were obtained in the axial plane only. Imaging sequences are reported in . Distance and cross sectional area (CSA) measurements were determined using distance and area tools within the imaging software (AGFA Healthcare, Mortsel, Belgium).

The following AT and calf muscle morphological features were evaluated bilaterally: maximum distance from the anterior to the posterior (MAD) boundaries of the AT (Figure 10); tendon length (distance from the distal soleus myotendinous junction to posterior superior margin of the calcaneal tuberosity) (Figure 11); CSA of the tendon at MAD (Figure 12); maximum gastrocnemius medialis, lateralis, and soleus CSA (Figure 13); gastrocnemius medialis, lateralis, and soleus CSA at a 15 cm distal to the inferior pole of the patella; maximum calf circumference (Figure 14); and calf circumference at 15 cm distal to the inferior pole of the patella.

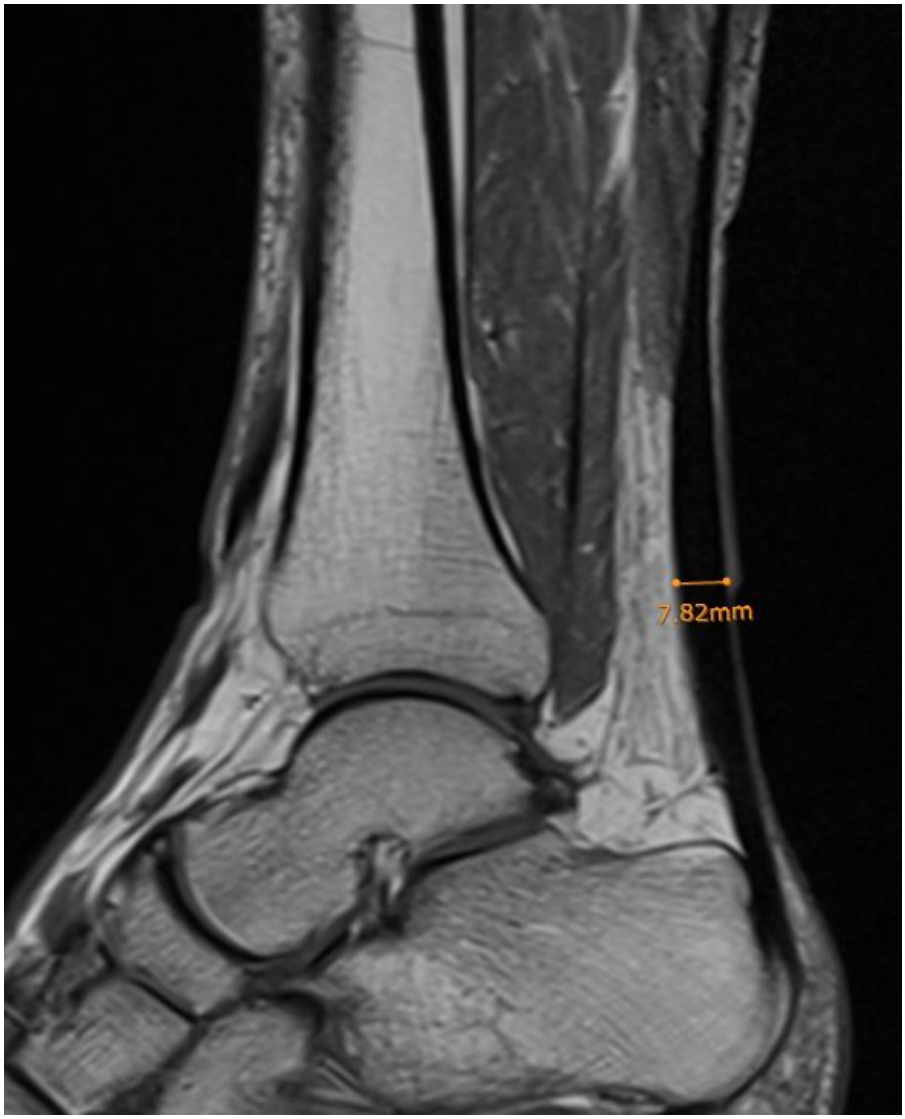


**Figure 10** Sagittal T1-weighted turbo spin echo magnetic resonance image demonstrating measurement of the maximum anteroposterior Achilles tendon diameter (orange)

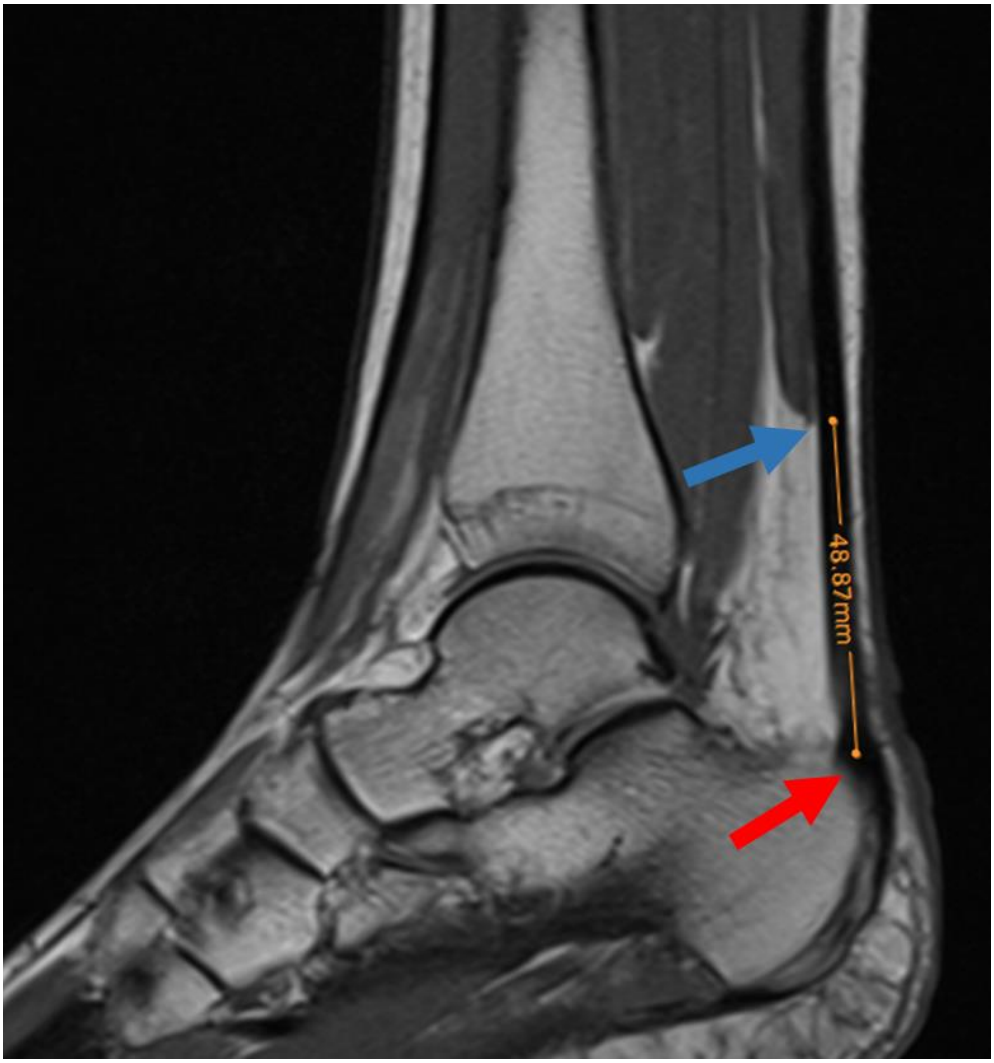


**Figure 11** Sagittal T1-weighted turbo spin echo magnetic resonance image demonstrating measurement of tendon length (orange) from distal soleus myotendinous junction (blue arrow) to the posterior superior margin of the calcaneus (red arrow)

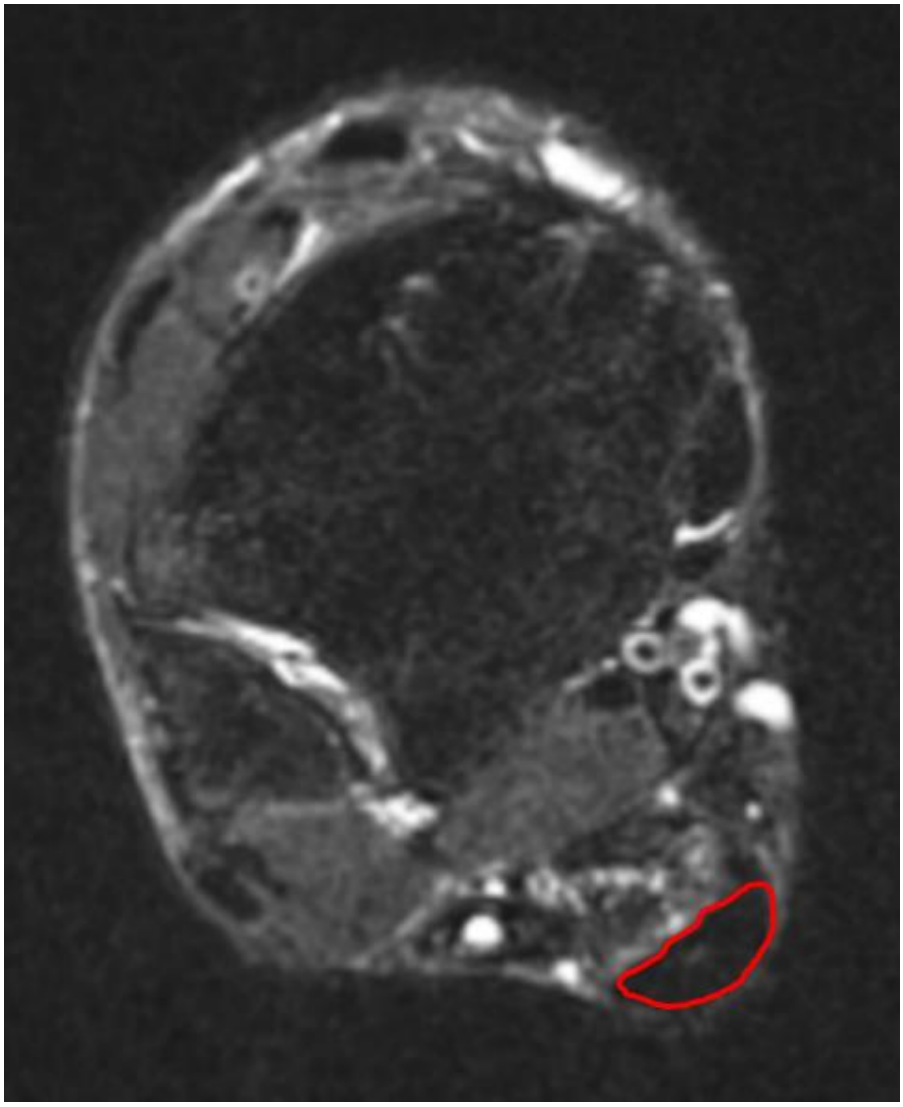

**Figure 12** Axial T2-weighted turbo spin echo fat saturated magnetic resonance image demonstrating the measurement of cross sectional area of the Achilles tendon at its maximum anteroposterior diameter (red)

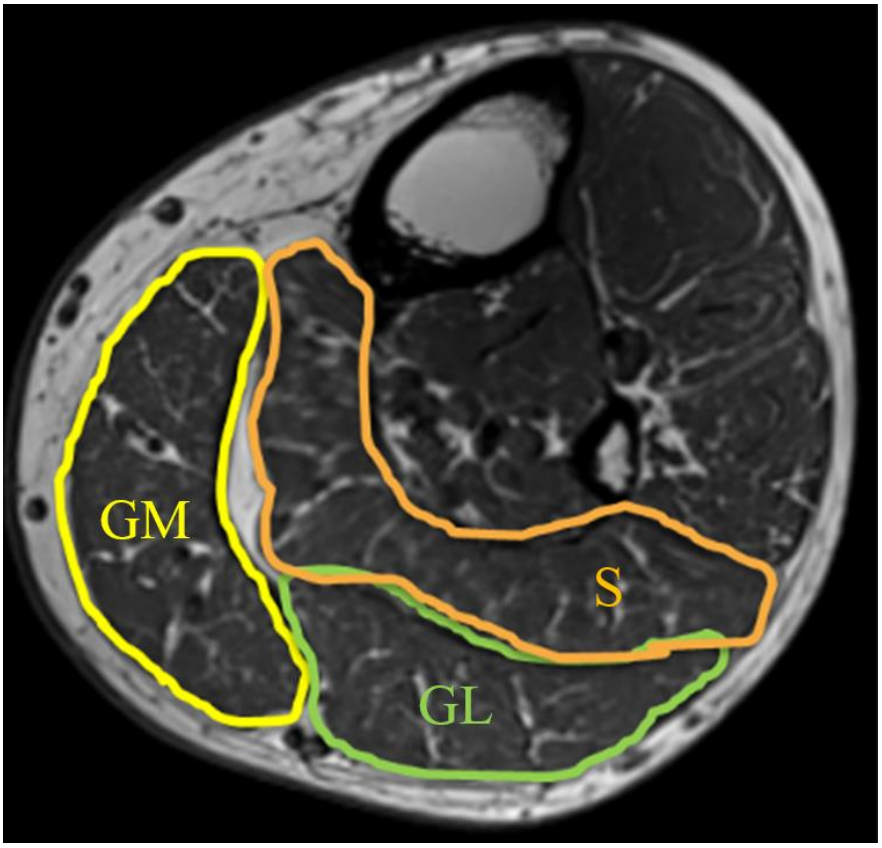


**Figure 13** Axial T2-weighted turbo spin echo fat saturated magnetic resonance image demonstrating cross sectional area measurement of the gastrocnemius medialis (GM, yellow), gastrocnemius lateralis (GL, green), and soleus (S, orange)

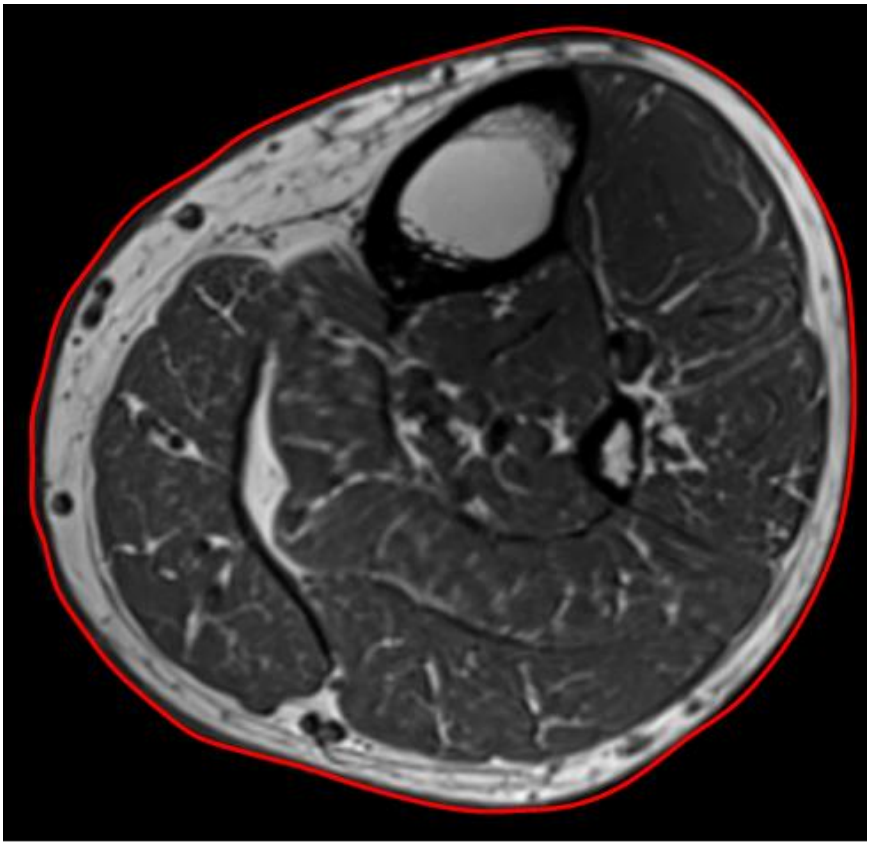

**Figure 14** Axial T2-weighted turbo spin echo fat saturated magnetic resonance image demonstrating calf circumference measurement (red)

## 4.4.2 Physical examination outcome measures

*Calf circumference*

Calf circumference was measured using a standard flexible measuring tape at a position 15 cm distal to the inferior pole of the patella while the participant was seated with their knee flexed at 90° (gastrocnemius relaxed) and hanging over the edge of a table (Figure 15). Calf circumference measurements have been shown to be reliable regardless of technique used (Carmont et al., 2013).

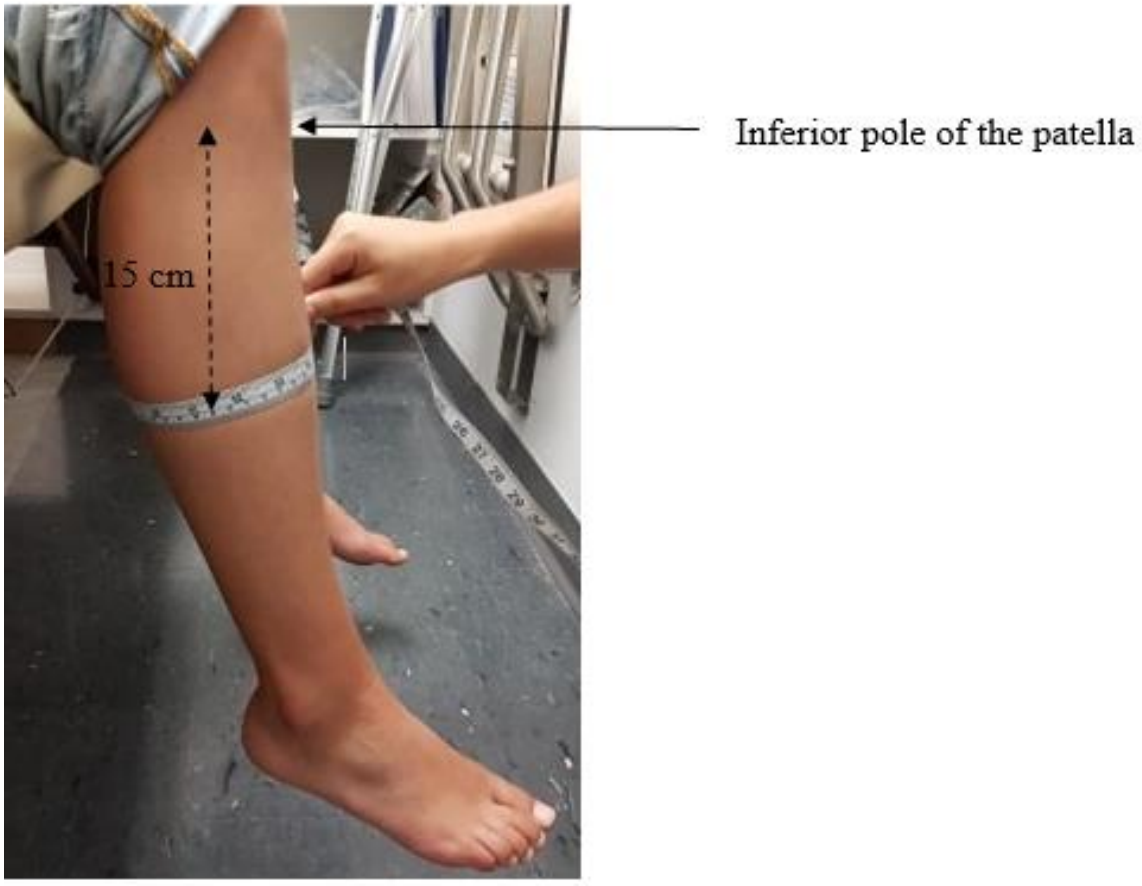


**Figure 15** Measurement of calf circumference at 15 cm distal to the inferior pole of the patella

*Plantar- and dorsiflexion active and passive range of motion*

Plantar- and dorsiflexion range of motion was evaluated using a standard goniometer while the patient was positioned supine with the knee flexed to 30°. The goniometer was placed on the participant such that the axis of rotation was just distal to the lateral malleolus, the fixed arm was aligned with the long axis of the fibula, and the moveable arm was positioned on the lateral border of the foot.

Firstly, the outcome assessor positioned the ankle joint in the neutral position (0°) (Figure 16). The participant was subsequently instructed to actively move into plantar- or dorsiflexion. Once the active range of motion measurement was recorded, the outcome assessor passively moved the ankle joint and the passive range of motion measurement was taken. This process was repeated three times on each limb, alternating from plantar- to dorsiflexion. Goniometric measures have shown high intra-rater reliability (Elveru et al., 1988).

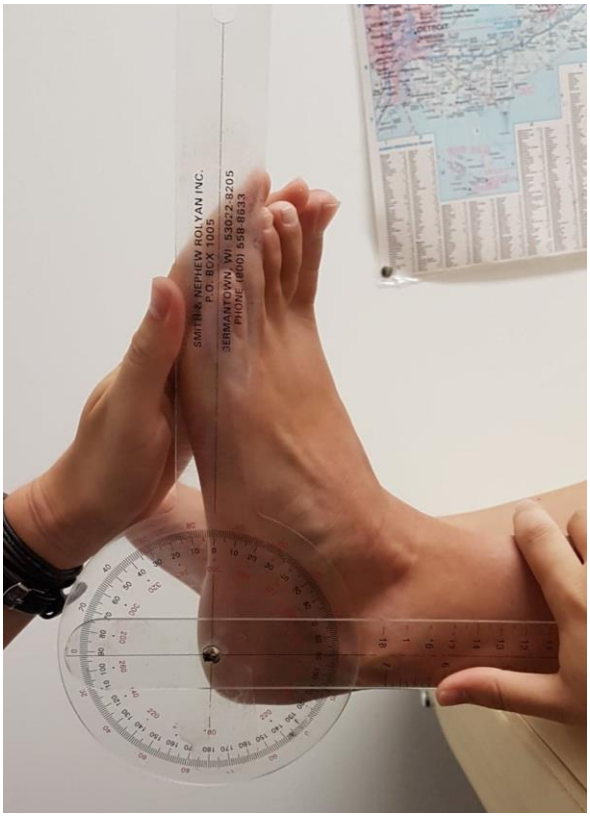


**Figure 16** Neutral (0°) position of the ankle

### 4.4.3 Performance-based outcome measures

*Maximum single-legged heel rise repetitions*

Participants performed maximal single-legged heel rises while standing barefoot on a box with an incline of 10° (Figure 17). Participants listened to a metronome (60 beats per minute) and were instructed to raise their heel as high as they could on the first beat, then lower to the starting position on the second beat. The test was terminated when the participant stopped, could not maintain the frequency of the metronome, or did not perform a proper heel rise (unable to raise heel more than 2 cm). Participants were permitted to rest two fingertips on the stabilizing bar on the front of the apparatus for balance. Total number of heel-rises was recorded. This test was created by Silbernagel et al. (2010) and has been shown to be reliable and valid for patients after AATR (Bostick et al., 2010; Brorsson et al., 2017; Powell et al., 2018; Silbernagel et al., 2012).

**Figure 17** Apparatus for the heel-rise test

*Plantar- and dorsiflexion isokinetic strength*

Plantar- and dorsiflexion isokinetic strength was assessed using a Biodex Multi-Joint System 3 Dynamometer (Biodex Medical, Shirley, New York) (Figure 18). Participants lay supine with their thigh supported by and fixed to a thigh rest to minimize upper leg involvement. The knee was flexed at approximately 20° and the lateral malleolus was aligned with the dynamometer's axis of rotation. The foot was fixed to the plate of the dynamometer using a Velcro strap and an ankle strap. Prior to beginning the isokinetic strength test, the upper and lower range of motion were set by asking the participant to maximally plantar- and dorsiflex while strapped into the Biodex. Torque measurements were measured within these limits.

Participants performed four maximal effort reciprocal plantar- and dorsiflexion movements at 30°/s and 60°/s, and 10 at 240°/s. A 1-minute rest period was given between test velocities. Peak plantar- and dorsiflexion torques (Nm) for each velocity were calculated by averaging peak torques of individual repetitions. The data collected were checked following each test to eliminate any unreliable results. We deemed the data unreliable if minimum and maximum values differed more than 10%. The test was repeated if necessary. When conducted this way, the test-retest reliability of isokinetic dynamometry is high (Moraux et al., 2013).

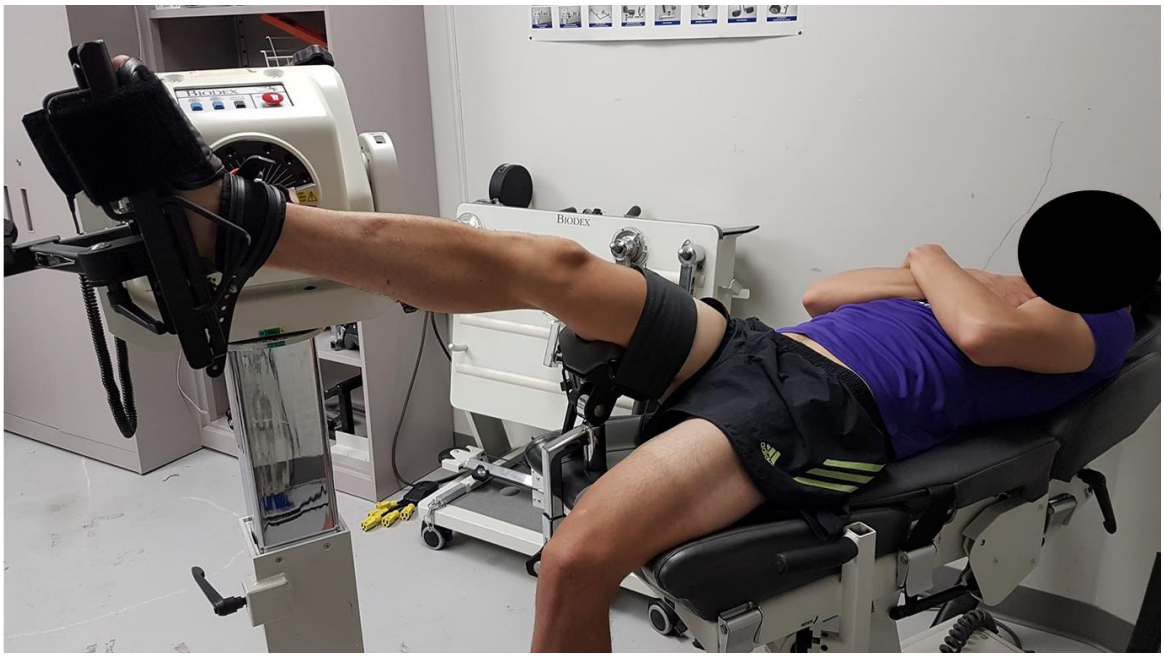


**Figure 18** The starting position for the isokinetic strength test on the Biodex Multi-Joint System 3 Dynamometer

*Maximum single-legged vertical jump*

Maximum single-legged vertical jump height was measured using a Vertical Challenger (Tandem Sport, Louisville, USA) (Figure 19). Starting from an upright standing position on one leg, participants made a downward movement by flexing at the ankles, knees, and hips. Participants then immediately extended their knees/hips to jump vertically from the ground and touched the Vertical Challenger with their fingers. Participants were permitted to land with two feet due to balance concerns. Three vertical jumps were performed on each limb in an alternating fashion.

**Figure 19** Vertical Challenger

*Gait analysis*

Participants underwent 3-dimensional quantitative gait analysis using a passive marker optical motion capture system consisting of 10 high speed cameras (Motion Analysis Corporation, Santa Rosa, CA, USA) and 3 force plates (OR6, AMTI) mounted flush with the ground. Twenty-two retro-reflective markers were placed on the participant's anatomical landmarks in accordance with a modified Helen Hayes configuration (Figure 20). Additional markers were placed over the medial knee joint line and the medial malleolus, bilaterally. An initial static standing trial was captured on the force plate to determine exact body mass and hip, knee, and ankle joint centres. The medial markers were removed prior to the walking trials. Participants were asked to walk barefoot at a self-selected pace across the 10-metre walkway until five successful force plates strikes were collected (i.e., the entire foot made contact with the plate, and there were no overtly

observed alterations in gait so as to hit the plate). Marker trajectories were captured at 60Hz, and ground reaction force data were recorded simultaneously at 1200Hz which was used to calculate plantar- and dorsiflexion moments (Cortex-64 4.0, Motion Analysis Corporation, Santa Rosa, CA, USA). The plantar- and dorsiflexion angles and moments were time normalized to 100% of stance (from initial heel-strike to toe-off). Moments were normalized to body weight and height (%BW·H). Peak values were identified and averaged over five trials.

Plantar- and dorsiflexion kinematics and kinetics included: maximum plantarflexion angle; maximum dorsiflexion angle; excursion (difference between maximum plantarflexion angle and maximum dorsiflexion angle); and peak plantarflexion moment). Temporospatial parameters included step length, stride length, and total support time (percent of total time spent in the stance phase).

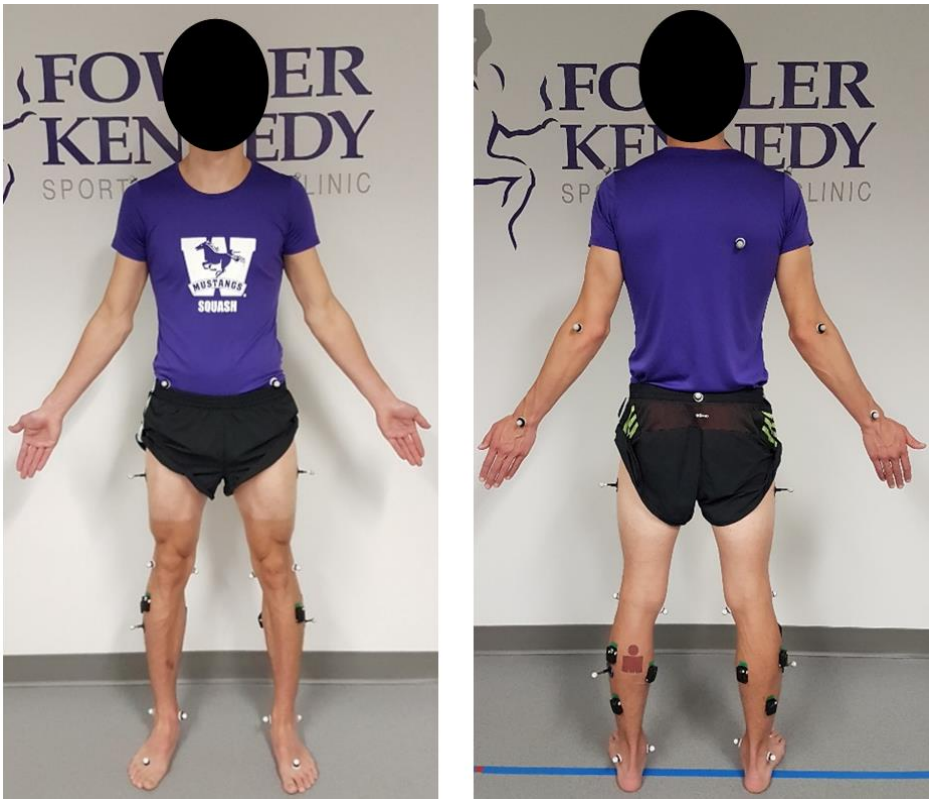


**Figure 20** Placement of retro-reflective markers on anatomical landmarks in the modified Helen Hayes configuration

### 4.4.4 Patient-reported outcome measures

Participants were asked to answer the subjective portions of the questionnaires based on their current symptoms (if any) in the involved limb from the initial Willits et al. 2010 study.

*Achilles Tendon Total Rupture Score*

The Achilles Tendon Total Rupture score (ATRS) (Appendix D) is an injury-specific outcome measure consisting of 10 items scored on a Likert scale between zero (severe limitations) and 10 (no limitations) (Nilsson-Helander et al., 2010). A maximum score of 100 indicates no symptoms or deficits in function. The ATRS is reported to be valid and reliable (Carmont et al., 2013).

*Leppilahti score*

The Leppilahti score (Appendix E) is a disease-specific outcome measure for AT rupture that combines subjective assessment of symptoms (pain, stiffness, calf muscle weakness, footwear restrictions, and satisfaction) and objective measures (ankle range of motion and isokinetic calf muscle strength) (Leppilahti et al., 1998). A score of 100 points represents the best possible score. Following instructions for the scale for the isokinetic strength item, the percent difference between the involved and uninvolved limb was converted to a point score. A maximum of 102 points represents normal ankle strength with no average torque deficit. Strength was graded using the following scores: excellent (87-102 points); good (72-86 points); fair (57-71 points); and poor (0-56 points). For the active range of motion item, the additive difference between each limb in plantar- and dorsiflexion was calculated and graded according to the following scores: normal (<6°); mild (6-10°); moderate (11-15°); and severe (>15°).

## 4.5 Statistical analysis

For each outcome measure assessed at final follow-up, we evaluated each limb separately, then calculated a side-to-side difference (involved limb subtracted by uninvolved limb). We compared limbs using dependent samples t-tests, and calculated

the standardized response mean (SRM) for each outcome. The involved limb and side-to-side difference measures were compared between treatment groups over time (from initial study to present follow-up) using a two-factor (group by time) analysis of variance (ANOVA). If there was a significant group by time interaction, we performed post hoc comparisons. 'Initial' study values represent the last outcome carried forward from the Willits et al. (2010) study, which was data primarily from the 2-year follow-up. We compared side-to-side difference between operative and non-operative groups using independent samples t-tests, and calculated the effect size (ES) for each outcome. An outcome 'favoured' a group if the side-to-side limb difference was smaller. Finally, we conducted post hoc analyses exploring the associations between involved limb MRI and performance-based outcome measures using Pearson product-moment correlation coefficients (r). All significance tests were two-sided with $p \leq 0.05$. We used SPSS version 26 (SPSS, Inc., Chicago, Illinois) for all analyses. Data are presented as the mean, standard deviation and mean difference with 95% confidence intervals for continuous variables. Frequencies are reported for nominal variables. Bolded values indicate a significant difference ($p \leq 0.05$).

# Chapter 5

# 5 Results

## 5.1 Participant flow

The flow of participants is outlined in Figure 21. We were able to contact 52 of the 80 original participants from this centre. Of those, nine declined participation. The remaining 43 participants consented (Appendix F) and were enrolled in the present study. Of those enrolled, eight were unable to visit the lab for testing due to location changes (i.e. moved from local area) (n=5) or other injuries unrelated to their AT (n=3). Patient-reported outcome measures were assessed over the telephone for those eight participants. Further, three participants were unable to undergo MRI: two ineligible due to MRI-incompatible hardware inside their bodies, and one due to a fear of confined spaces. These participants completed the study excluding the MRI portion.

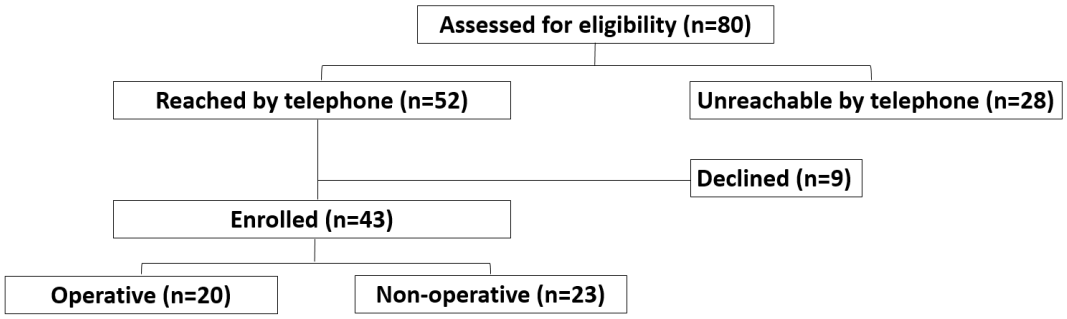


**Figure 21** Participant flow

## 5.2 Participant characteristics

Participant demographic information is provided in Table 1. Characteristics were similar between groups. Time from rupture in the final follow-up ranged from 13 to 18 years. One participant in each group sustained a re-rupture in their involved limb from the Willits et al. (2010) study. Both of these re-ruptures occurred within the first 3 months of the initial rupture and followed the treatment plan that they were initially randomized to. In the operative group, four participants sustained contralateral ruptures since the final

follow-up (2 years post-injury) of the Willits et al. (2010) study. Data from these four participants that compared side-to-side differences were not included in analysis of the outcomes in the present study.

**Table 1** Patient demographics at final follow-up

*Abbreviations:* SD = standard deviation; ADL = activities of daily living

*Not identified for 4 participants

| Characteristic | Total (n=43) | Operative (n=20) | Non-operative (n=23) |
|---|---|---|---|
| Sex, male/female | 29/14 | 13/7 | 16/7 |
| Age, y | 57.3 ± 7.8 | 54.9 ± 8.3 | 59.4 ± 6.8 |
| Height, m | 1.77 ± 0.1 | 1.80 ± 0.1 | 1.75 ± 0.1 |
| Weight, kg | 91.7 ± 18.0 | 94.4 ± 18.3 | 89.4 ± 18.0 |
| Body mass index, kg/m$^2$ | 29.1 ± 4.6 | 29.2 ± 5.4 | 29.0 ± 3.9 |
| Time from initial rupture to follow-up, y | 14.7 ± 1.4 | 15.1 ± 1.4 | 14.4 ± 1.4 |
| Initial study involved limb, left/right | 28/15 | 13/7 | 15/8 |
| Dominant limb, left/right* | 2/37 | 1/17 | 1/20 |
| Number of re-ruptures in the initial study limb | 2 | 1 | 1 |
| Number of ruptures in contralateral limb | 4 | 4 | 0 |
| Activity at injury, sports/ADL | 38/5 | 18/2 | 20/3 |

## 5.3 Outcome measures

### 5.3.1 MRI outcome measures

The MRI results describing AT morphology are reported in Table 2. With the exception of CSA of the AT at the MAD in the operative group, there were substantial differences between limbs in all outcomes. The AT can be described as thicker (Figure 22) and longer (Table 2), with the SRM describing the size of the difference ranging from 0.76 to 5.06. The only difference between treatment groups was in the MAD, which favoured non-operatively treated participants (ES=1.32). The ES describing the size of the difference between treatment groups for MRI Achilles tendon measures ranged from 0.03 to 1.32.

**Table 2** Between-limb and between-group comparisons of Achilles tendon magnetic resonance imaging outcomes at final follow-up

*Abbreviations:* MAD = maximum anteroposterior diameter; AT; Achilles tendon; CSA = cross sectional area

*differences between treatment groups in the side-to-side difference between limbs

| Outcome Measures | Total (n=28) | | | Operative (n=11) | | | Non-operative (n=17) | | | Between-groups* |
|---|---|---|---|---|---|---|---|---|---|---|
| | *Involved* | *Uninvolved* | *Difference (95% CI), p value* | *Involved* | *Uninvolved* | *Difference (95% CI), p value* | *Involved* | *Uninvolved* | *Difference (95% CI), p value* | *Difference (95% CI), p value* |
| MAD, mm | 13.7 ± 1.9 | 7.2 ± 1.6 | 6.5 (5.7 – 7.5), **<0.01** | 14.9 ± 1.6 | 6.9 ± 1.2 | 7.9 (6.9 – 9.0), **<0.01** | 13.0 ± 1.6 | 7.3 ± 1.8 | 5.6 (4.7 – 6.6), **<0.01** | 2.2 (0.9 – 3.7), **0.003** |
| AT length, mm | 73.6 ± 20.7 | 52.6 ± 19.2 | 21.0 (12.3 – 29.8), **<0.01** | 68.8 ± 15.4 | 47.4 ± 14.4 | 21.4 (12.4 – 30.4), **<0.01** | 76.7 ± 23.5 | 55.9 ± 21.5 | 20.8 (6.7 – 34.9), **0.007** | 0.6 (-15.4 – 16.6), 0.938 |
| CSA of AT at the MAD, $cm^2$ | 3.2 ± 5.0 | 1.0 ± 0.5 | 2.1 (0.1 – 4.1), **0.036** | 5.1 ± 8.1 | 0.8 ± 0.3 | 4.3 (-1.4 – 10.0), 0.125 | 2.0 ± 0.7 | 1.1 ± 0.6 | 0.9 (0.4 – 1.3), **0.001** | 3.4 (-2.3 – 9.1), 0.214 |

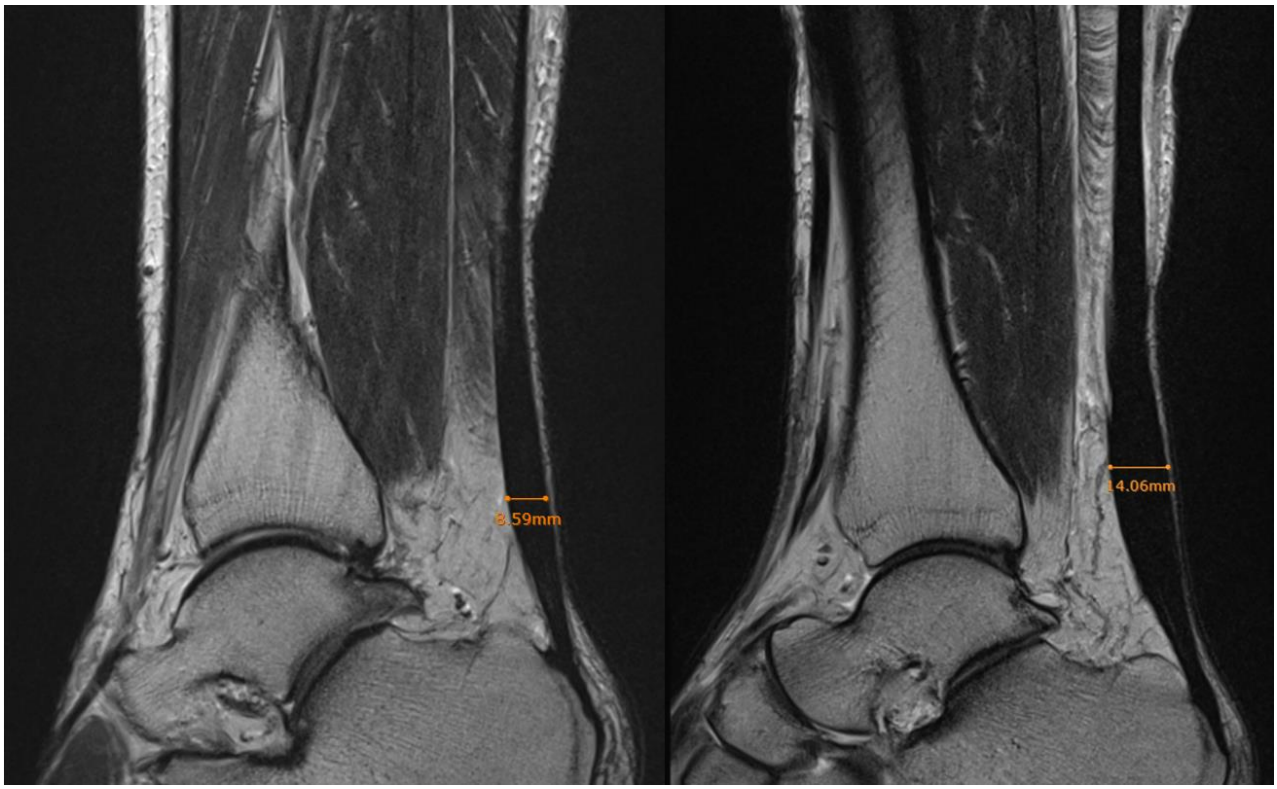


**Figure 22** Sagittal T1-weighted turbo spin echo magnetic resonance image in a representative participant illustrating maximum anteroposterior Achilles tendon diameter (orange) for the uninvolved (left) and involved (right) limbs

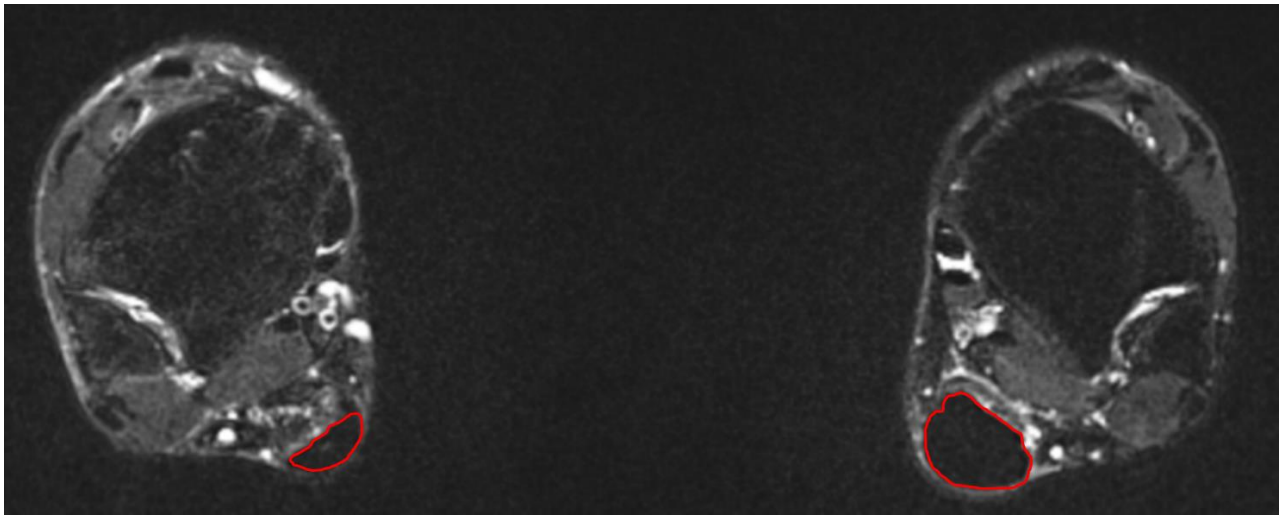

**Figure 23** Axial T2-weighted turbo spin echo fat saturated magnetic resonance image in a representative participant illustrating maximum Achilles tendon cross-sectional area (red) in the uninvolved (left) and involved (right) limbs

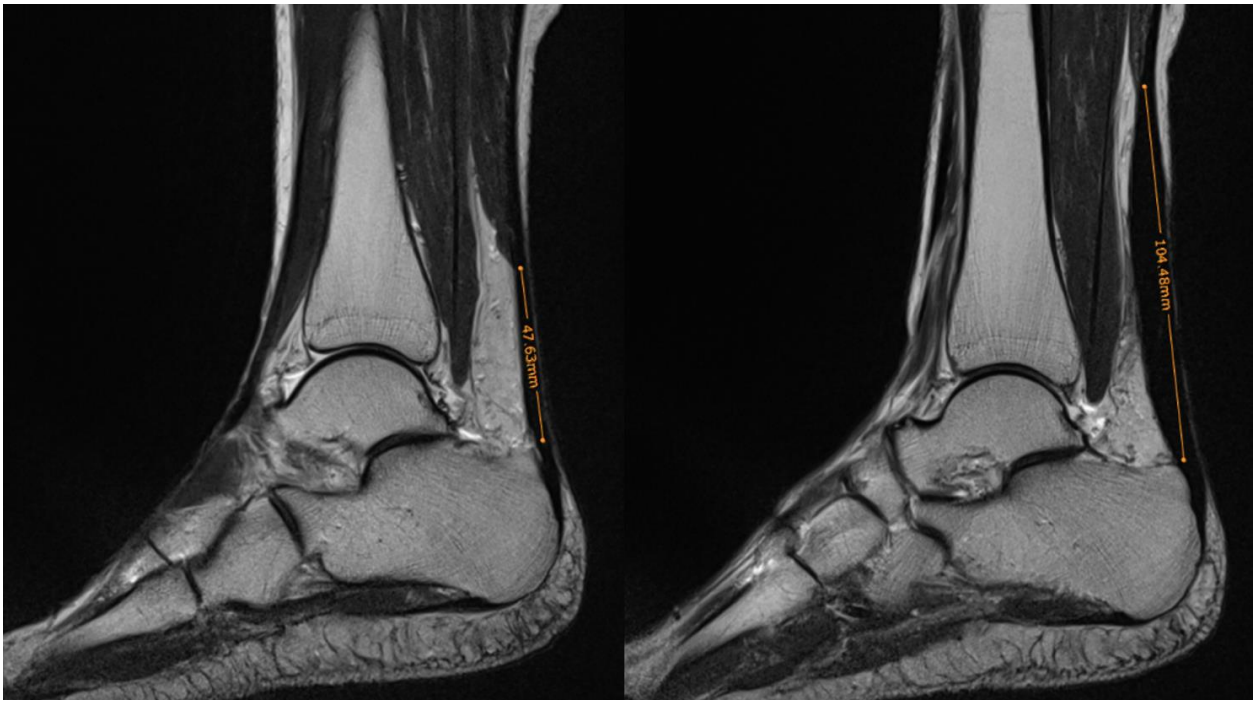


**Figure 24** Sagittal T1-weighted turbo spin echo magnetic resonance image in a representative participant illustrating Achilles tendon length (orange) for the uninvolved (left) and involved limbs (right)

The MRI results describing calf muscle morphology at maximum calf circumference are reported in Table 3. With the exception of gastrocnemius lateralis and calf circumference in the operative group, triceps surae CSA (Figure 25) and calf circumference (Figure 26) were smaller in the involved compared to the uninvolved limb. The SRM describing the size of the difference ranged from 0.54 to 1.71. The ES describing the size of the difference between treatment groups for MRI calf measures at maximum calf circumference ranged from 0.13 to 0.75.

The MRI results describing calf muscle morphology at 15 cm distal to the inferior pole of the patella are reported in Table 4. With the exception of calf circumference in the operative group, triceps surae CSA and calf circumference were smaller in the involved compared to the uninvolved limb. The SRM describing the size of the difference ranged from 0.62 to 1.97. The ES describing the size of the difference between treatment groups for MRI calf measures at 15 cm distal to the inferior pole of the patella ranged from 0.08 to 0.71.

**Table 3** Between-limb and between-group comparisons of maximum bulk lower leg magnetic resonance imaging findings at final follow-up

*Abbreviations:* CSA = cross sectional area; MG = medial gastrocnemius; LG = lateral gastrocnemius

*differences between treatment groups in the side-to-side difference between limbs

| Outcome Measures | Total (n=28) | | | Operative (n=11) | | | Non-operative (n=17) | | | Between-groups * |
|---|---|---|---|---|---|---|---|---|---|---|
| | *Involved* | *Uninvolved* | *Difference (95% CI), p value* | *Involved* | *Uninvolved* | *Difference (95% CI), p value* | *Involved* | *Uninvolved* | *Difference (95% CI), p value* | *Difference (95% CI), p value* |
| Maximum MG CSA, $cm^2$ | 12.2 ± 3.9 | 16.5 ± 4.4 | -4.3 (-5.4 - -3.3), **<0.01** | 11.8 ± 3.8 | 16.4 ± 3.4 | -4.6 (-6.3 - -2.8), **<0.01** | 12.4 ± 4.1 | 16.6 ± 5.1 | -4.2 (-5.7 - -2.7), **<0.01** | 0.4 (-1.9 – 2.6), 0.747 |
| Maximum LG CSA, $cm^2$ | 7.1 ± 2.5 | 9.0 ± 2.6 | -2.0 (-2.8 - -1.1), **<0.01** | 7.6 ± 3.0 | 9.1 ± 3.1 | -1.6 (-3.3 – 0.1), 0.057 | 6.7 ± 2.2 | 8.9 ± 2.2 | -2.1 (-3.2 - -1.2), **<0.01** | 0.6 (-1.1 – 2.3), 0.495 |
| Maximum soleus CSA, $cm^2$ | 18.1 ± 5.2 | 22.3 ± 5.9 | -4.3 (-5.6 - -3.0), **<0.01** | 18.7 ± 5.9 | 23.2 ± 6.2 | -4.5 (-6.4 - -2.6), **<0.01** | 17.6 ± 4.9 | 21.8 ± 5.8 | -4.1 (-6.0 - -2.3), **<0.01** | 1.2 (-2.0 – 4.3), 0.454 |
| Maximum calf circumference, cm | 39.0 ± 4.1 | 40.5 ± 4.1 | -1.5 (-2.1 - -1.0), **<0.01** | 40.4 ± 4.6 | 41.3 ± 4.8 | -0.9 (-2.0 – 0.2), 0.102 | 38.1 ± 3.5 | 40.0 ± 3.7 | -1.9 (-2.5 - -1.4), **<0.01** | 1.0 (0.0 – 2.1), 0.058 |

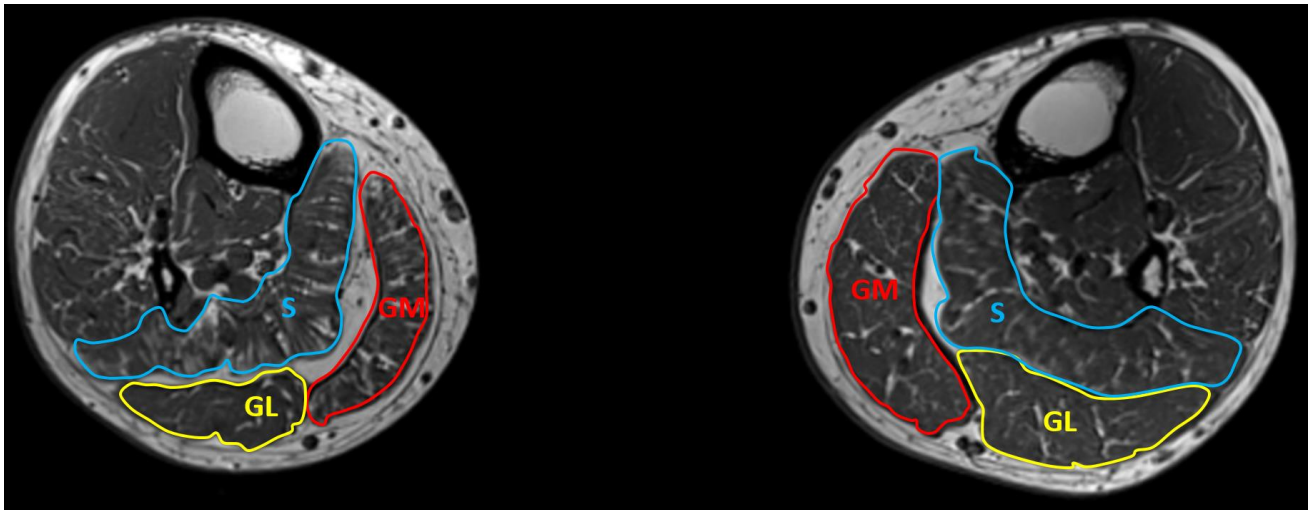


**Figure 25** Axial T2-weighted turbo spin echo fat saturated magnetic resonance image in a representative patient illustrating gastrocnemius medialis (GM, red), lateralis (GL, yellow), and soleus (S, blue) cross sectional area for the involved (left) and uninvolved (right) limbs

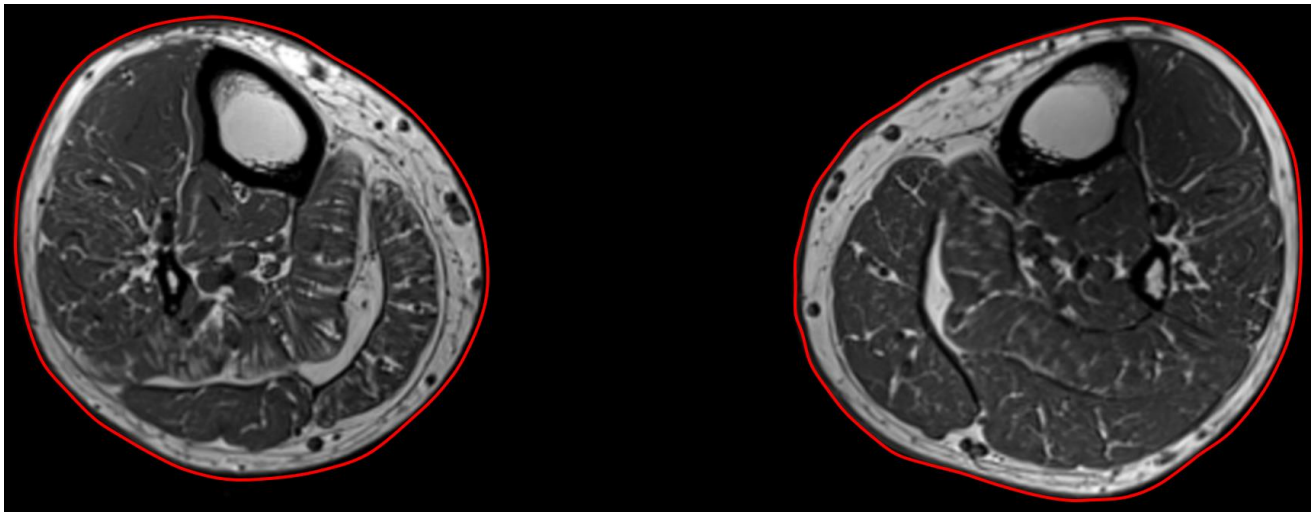

**Figure 26** Axial T2-weighted turbo spin echo fat saturated magnetic resonance image in a representative patient illustrating calf circumference (red) for the involved (left) and uninvolved (right) limbs

**Table 4** Between-limb and between-group comparisons of lower leg magnetic resonance imaging findings 15 cm distal to the inferior pole of the patella at final follow-up

*Abbreviations:* CSA = cross sectional area; MG = medial gastrocnemius; LG = lateral gastrocnemius

*differences between treatment groups in the side-to-side difference between limbs

| Outcome Measures | Total (n=28) | | | Operative (n=11) | | | Non-operative (n=17) | | | Between-groups* |
|---|---|---|---|---|---|---|---|---|---|---|
| | *Involved* | *Uninvolved* | *Difference (95% CI), p value* | *Involved* | *Uninvolved* | *Difference (95% CI), p value* | *Involved* | *Uninvolved* | *Difference (95% CI), p value* | *Difference (95% CI), p value* |
| MG CSA at 15 cm distal from the inferior pole of the patella, $cm^2$ | 10.2 ± 4.4 | 14.6 ± 4.6 | -4.4 (-5.7 - - 3.1), **<0.01** | 8.7 ± 3.4 | 13.8 ± 3.1 | -5.1 (-6.9 - - 3.4), **<0.01** | 11.2 ± 4.8 | 15.1 ± 5.3 | -3.9 (-5.9 - - 2.0), **0.001** | 0.3 (-2.7 – 3.4), 0.833 |
| LG CSA at 15 cm distal from the inferior pole of the patella, $cm^2$ | 5.2 ± 3.0 | 7.3 ± 2.9 | -2.0 (-2.9 – - 1.2), **<0.01** | 5.0 ± 3.4 | 6.7 ± 2.9 | -1.7 (-3.1 – - 0.2), **0.03** | 5.3 ± 2.8 | 7.6 ± 2.9 | -2.3 (-3.4 - - 1.1), **0.001** | 0.6 (-1.2 – 2.4), 0.486 |
| Soleus CSA at 15 cm distal from the inferior pole of the patella, $cm^2$ | 18.8 ± 5.5 | 22.7 ± 6.6 | -3.9 (-5.6 - - 2.1), **<0.01** | 19.8 ± 6.0 | 24.7 ± 7.0 | -4.9 (-6.9 - - 2.9), **<0.01** | 18.2 ± 5.2 | 21.5 ± 6.1 | -3.2 (-5.9 - - 0.5), **0.021** | 1.7 (-1.9 – 5.2), 0.351 |
| Calf circumference at 15 cm distal from the inferior pole of the patella, cm | 38.2 ± 4.0 | 40.0 ± 3.9 | -1.8 (-2.3 - - 1.2), **<0.01** | 39.6 ± 3.7 | 40.7 ± 4.1 | -1.1 (-2.3 – 0.0), 0.051 | 37.3 ± 3.9 | 39.5 ± 3.8 | -2.1 (-2.8 - - 1.6), **<0.01** | 1.0 (-0.1 – 2.3), 0.069 |

### 5.3.2 Physical examination outcome measures

*Calf circumference*

Calf circumference was smaller in the involved compared to the uninvolved limb, with the SRM describing the size of the difference ranging from 0.96 to 1.18 (Table 5). The ES describing the size of the difference between treatment groups was 0.28. The ANOVA indicated no statistically significant main effect for time (p=0.593), group (p=0.252), or time by group interaction (p=0.306) (Figure 27) in the involved limb. Similarly, there was no statistically significant main effect for time (p=0.457), group (p=0.558), or time by group interaction (p=0.552) when the side-to-side difference in calf circumference was compared to initial study values (Figure 28).

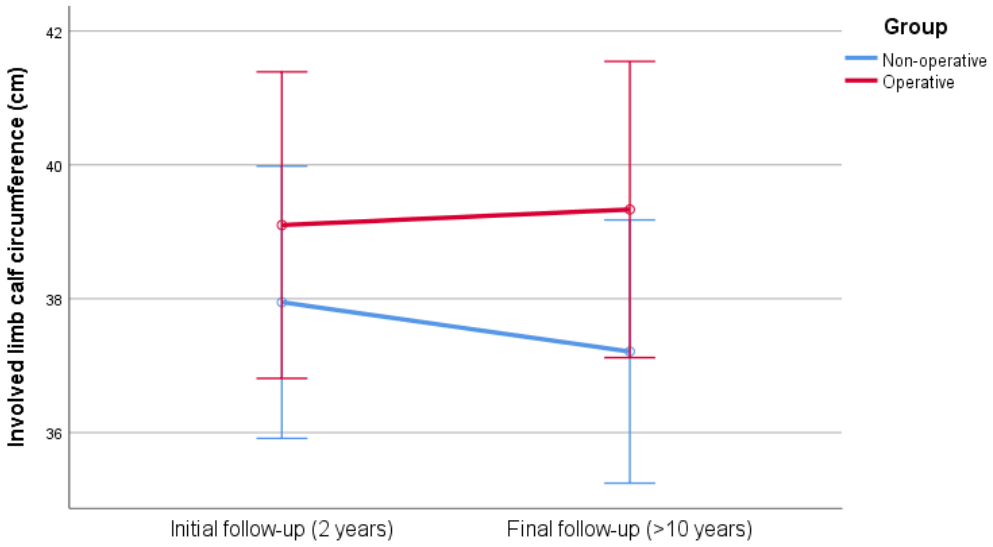


**Figure 27** Involved limb calf circumference for the operative (n=15) and non-operative (n=19) groups at the initial follow-up (2 years) and final follow-up (>10 years) post-rupture

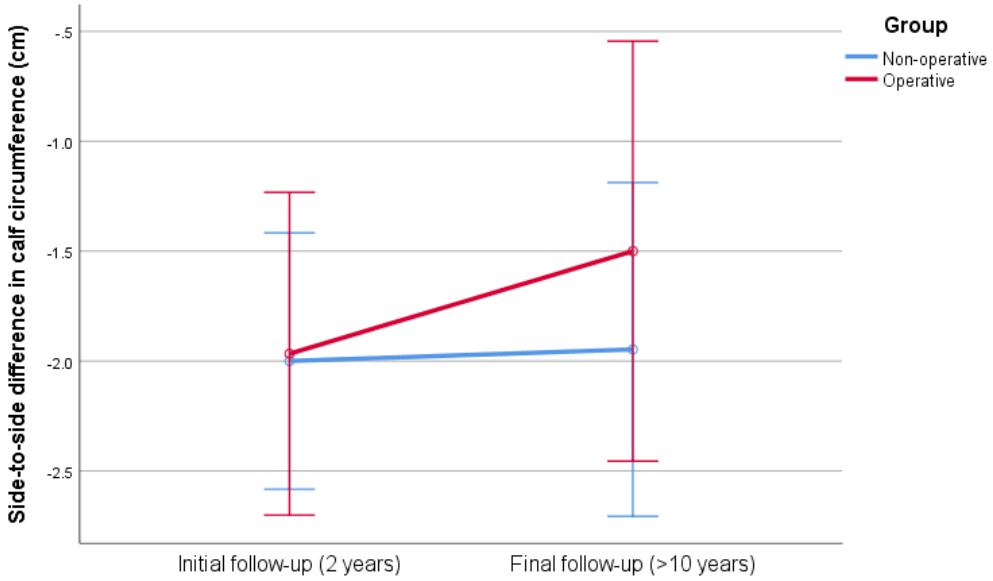


**Figure 28** Side-to-side differences calf circumference for the operative (n=12) and non-operative (n=19) groups at the initial follow-up (2 years) and final follow-up (>10 years) post-rupture

*Plantar- and dorsiflexion active and passive range of motion*

The results describing plantar- and dorsiflexion active and passive range of motion are reported in Table 5. Excluding the patients in the operative group, plantarflexion was smaller and dorsiflexion was larger in the involved compared to the uninvolved limb. The SRM describing the size of the difference ranged from 0.19 to 0.80. The ES describing the size of the difference between treatment groups for active and passive plantarflexion and dorsiflexion ranged from 0.09 to 0.52.

For active plantarflexion range of motion, when the involved limb was compared to initial study values, the ANOVA indicated a statistically significant main effect for time ($p=0.006$), and no statistically significant main effect for group ($p=0.642$) or time by group interaction ($p=0.333$) (Figure 29). Similarly, when the side-to-side difference was compared to initial study values, there was a statistically significant main effect for time ($p=0.045$), and no statistically significant effect for group ($p=0.424$) or time by group interaction ($p=0.080$) (Figure 30).

For active dorsiflexion range of motion, when the involved limb was compared to initial study values, there was a statistically significant main effect for time ($p=0.021$), no statistically significant main effect for group ($p=0.320$), and no statistically significant time by group interaction ($p=0.264$) (Figure 31). When the side-to-side difference was compared to initial study values, there was a statistically significant main effect for time ($p=0.002$), and no statistically significant main effect for group ($p=0.954$) or time by group interaction ($p=0.438$) (Figure 32).

**Table 5** Between-limb and between-group comparisons of physical assessment outcomes at final follow-up

*Abbreviations:* PF = plantarflexion; DF = dorsiflexion; AROM = active range of motion; PROM = passive range of motion

*differences between treatment groups in the side-to-side difference between limbs

| Outcome Measures | Total (n=31) | | | Operative (n=12) | | | Non-operative (n=19) | | | Between-group* |
|---|---|---|---|---|---|---|---|---|---|---|
| | *Involved* | *Uninvolved* | *Difference (95% CI), p value* | *Involved* | *Uninvolved* | *Difference (95% CI), p value* | *Involved* | *Uninvolved* | *Difference (95% CI), p value* | *Difference (95% CI), p value* |
| Calf circumference, cm | 38.1 ± 4.4 | 39.9 ± 4.2 | -1.8 (-2.4 - -1.2), **<0.01** | 39.6 ± 4.6 | 41.1 ± 4.4 | -1.5 (-2.5 - -0.5), **0.007** | 37.2 ± 4.2 | 39.2 ± 4.1 | -1.9 (-2.7 - .1.1), **<0.01** | 0.4 (-0.8 -1.7), 0.459 |
| PF AROM, ° | 40.6 ± 12.5 | 45.5 ± 9.9 | -4.9 (-8.3 - -1.5), **0.007** | 42.4 ± 14.3 | 44.3 ± 12.2 | -1.9 (-8.5 – 4.6), 0.528 | 39.5 ± 11.6 | 46.2 ± 8.5 | -6.8 (-10.8 - -2.7), **0.002** | 4.8 (-2.1 – 11.8), 0.165 |
| DF AROM, ° | 15.8 ± 3.7 | 13.3 ± 3.7 | 2.5 (0.9 – 4.2), **0.004** | 15.3 ± 3.0 | 12.4 ± 4.0 | 2.9 (-0.4 – 6.2), 0.081 | 16.1 ± 4.1 | 13.9 ± 3.5 | 2.3 (0.3 – 4.3), **0.026** | 0.6 (-2.8 – 4.0), 0.720 |
| PF PROM, ° | 43.6 ± 12.7 | 48.4 ± 10.5 | -4.8 (-8.3 - -1.3), **0.009** | 44.7 ± 14.4 | 47.1 ± 12.7 | -2.4 (-9.4 – 4.7), 0.471 | 43.0 ± 12.0 | 49.3 ± 9.1 | -6.3 (-10.3 - -2.2), **0.004** | 3.9 (-3.2 – 11.0), 0.272 |
| DF PROM, ° | 18.1 ± 3.5 | 15.5 ± 3.7 | 2.6 (1.0 – 4.1), **0.002** | 17.6 ± 2.7 | 14.7 ± 3.8 | 2.8 (-0.2 – 5.9), 0.064 | 18.5 ± 4.0 | 16.1 ± 3.6 | 2.4 (0.5 – 4.3), **0.015** | 0.4 (-2.8 – 3.6), 0.794 |

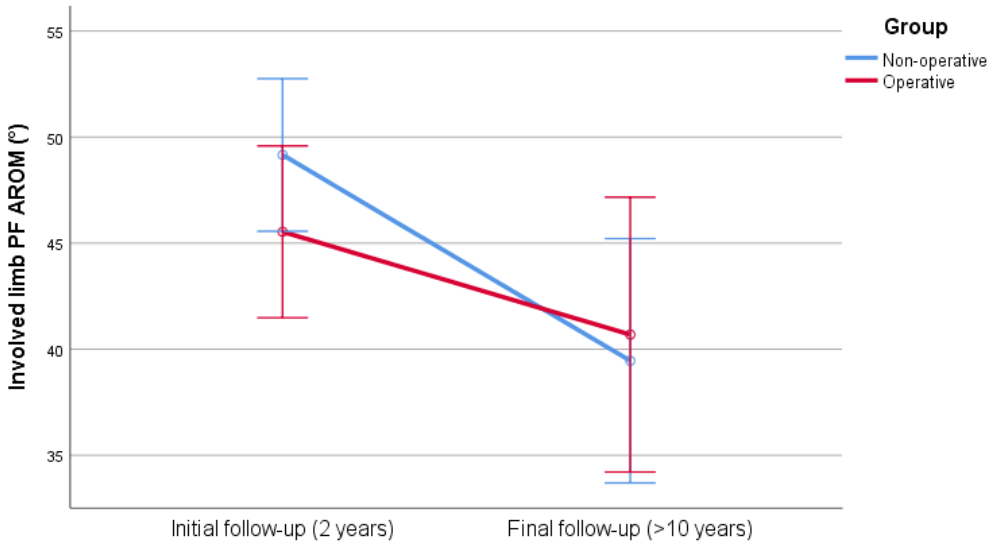


**Figure 29** Involved limb plantarflexion active range of motion (PF AROM) for the operative (n=15) and non-operative (n=19) groups at the initial follow-up (2 years) and final follow-up (>10 years) post-rupture

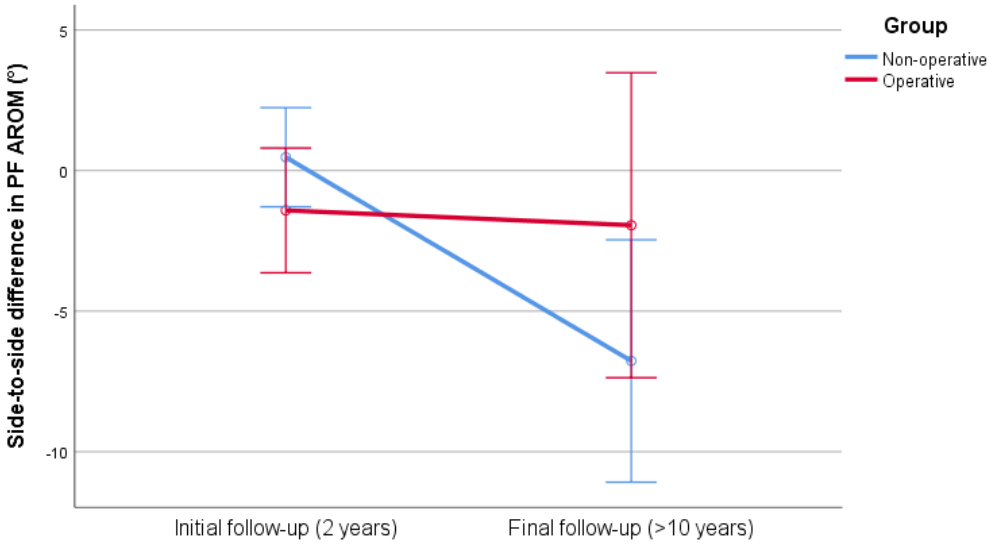


**Figure 30** Side-to-side differences in plantarflexion range of motion (PF AROM) for the operative (n=12) and non-operative (n=19) groups at the initial follow-up (2 years) and final follow-up (>10 years) post-rupture

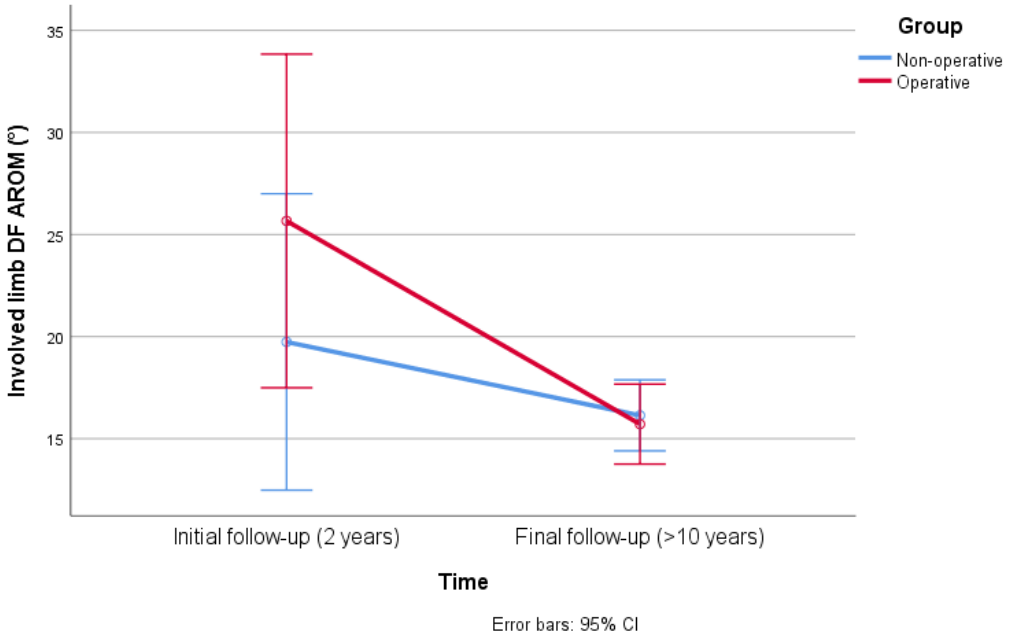


**Figure 31** Involved limb dorsiflexion active range of motion (DF AROM) for the operative (n=15) and non-operative (n=19) groups at the initial follow-up (2 years) and final follow-up (>10 years) post-rupture

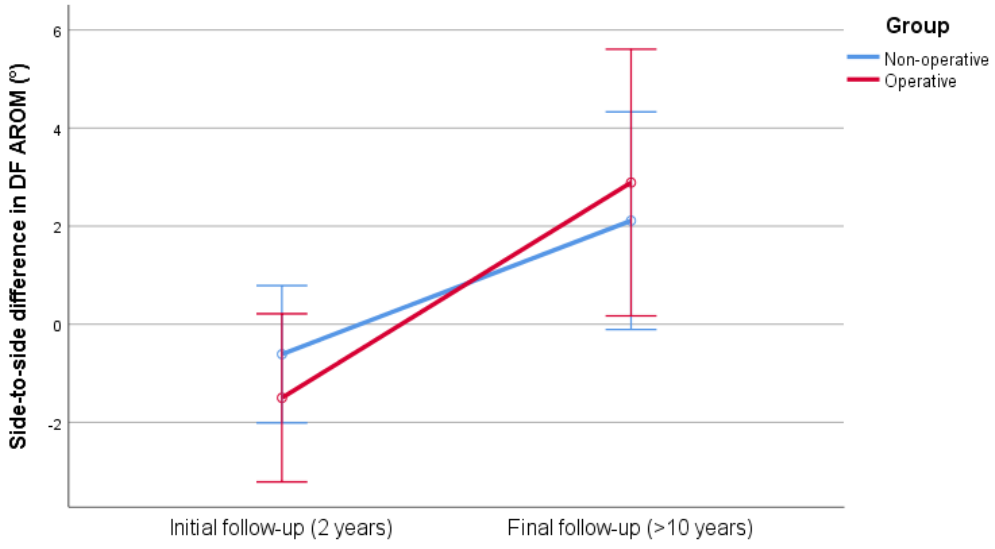


**Figure 32** Side-to-side differences in dorsiflexion active range of motion (DF AROM) for the operative (n=12) and non-operative (n=18) groups at the initial follow-up (2 years) and final follow-up (>10 years) post-rupture

### 5.3.3 Performance-based outcome measures

*Maximum single-legged heel rise repetitions*

The results describing maximum single-legged heel rise repetitions are reported in Table 6. More heel-rises were performed on the uninvolved compared to the involved limb, with statistically significant differences in the operative group. The SRM describing the size of the difference ranged from 0.18 to 0.69. The ES describing the size of the difference between treatment groups was 0.2.

*Maximum single-legged vertical jump*

The results describing maximum single-legged vertical jump height are reported in Table 6. Participants jumped higher with their uninvolved compared to their involved limb. The SRM describing the size of the difference ranged from 0.43 to 0.54. The ES describing the size of the difference between treatment groups was 0.1.

**Table 6** Between-limb and between-group differences in heel-rise repetitions and maximum vertical jump height at final follow-up

*differences between treatment groups in the side-to-side difference between limbs

| Outcome measures | Total (n=31) | | | Operative (n=12) | | | Non-operative (n=19) | | | Between-group* |
|---|---|---|---|---|---|---|---|---|---|---|
| | *Involved* | *Uninvolved* | *Difference (95% CI), p value* | *Involved* | *Uninvolved* | *Difference (95% CI), p value* | *Involved* | *Uninvolved* | *Difference (95% CI), p value* | *Difference (95% CI), p value* |
| Heel-rise repetitions | 21.6 ± 12.8 | 23.8 ± 8.2 | -2.2 (-5.2 – 0.8), 0.145 | 19.9 ± 8.0 | 23.0 ± 8.8 | -3.1 (-6.1 - -0.1), **0.046** | 22.6 ± 15.0 | 24.3 ± 8.1 | -1.7 (-6.3 – 2.9), 0.455 | 1.4 (-4.9 – 7.7), 0.652 |
| Maximum vertical jump, in | 7.9 ± 2.4 | 8.4 ± 2.4 | -0.5 (-0.8 - -0.1), **0.013** | 7.3 ± 2.0 | 7.9 ± 2.3 | -0.6 (-1.3 – 0.1), 0.089 | 8.4 ± 2.6 | 8.7 ± 2.4 | -0.4 (-0.8 – 0.1), 0.086 | 0.2 (-0.5 – 1.0), 0.514 |

*Gait analysis*

The results for plantar- and dorsiflexion angles and moments, and temporospatial gait parameters are reported in Table 7 and Table 8, respectively. There were no statistically significant differences between limbs or between treatment groups for any gait measure. The SRM describing the size of the difference ranged from 0.002 to 0.42. The ES describing the size of the difference between treatment groups for gait measures ranged from 0.10 to 0.39.

**Table 7** Between-limb and between-group differences in plantar- and dorsiflexion angles and moments during gait at final follow-up

*Abbreviations:* PF = plantarflexion; DF = dorsiflexion; BW = body weight; H = height
*differences between treatment groups in the side-to-side difference between limbs

| Outcome measures | Total (n=30) | | | Operative (n=10) | | | Non-operative (n=20) | | | Between-groups* |
|---|---|---|---|---|---|---|---|---|---|---|
| | *Involved* | *Uninvolved* | *Difference (95% CI), p value* | *Involved* | *Uninvolved* | *Difference (95% CI), p value* | *Involved* | *Uninvolved* | *Difference (95% CI), p value* | *Difference (95% CI), p value* |
| Maximum PF angle, ° | 11.4 ± 4.5 | 10.7 ± 3.7 | 0.8 (-0.8 – 2.3), 0.317 | 12.9 ± 5.1 | 12.7 ± 3.4 | 0.2 (-3.1 – 3.5), 0.898 | 10.6 ± 4.1 | 9.5 ± 3.4 | 1.1 (-0.7 – 2.9), 0.392 | 1.6 (-1.7 – 4.8), 0.339 |
| Maximum DF angle, ° | 11.3 ± 5.3 | 12.5 ± 4.9 | -1.5 (-2.4 – 0.1), 0.073 | 10.1 ± 5.3 | 11.3 ± 5.0 | -1.2 (-4.2 – 1.9), 0.408 | 12.1 ± 5.2 | 13.2 ± 4.8 | -1.1 (-2.4 – 0.2), 0.837 | 1.3 (-3.8 – 1.6), 0.409 |
| Excursion, ° | 22.8 ± 4.7 | 23.2 ± 5.4 | -0.4 (-1.8 – 1.0), 0.577 | 23.0 ± 4.7 | 24.0 ± 6.3 | -1.0 (-3.5 – 1.5), 0.406 | 22.6 ± 4.9 | 22.7 ± 4.8 | 0.0 (-1.9 – 1.8), 0.287 | 1.5 (-2.6 – 3.5), 0.763 |
| Peak PF moment, % BW•H | 1.4 ± 0.2 | 1.4 ± 0.2 | 0.0 (-0.04 – 0.1), 0.955 | 1.4 ± 0.3 | 1.4 ± 0.3 | 0.0 (-0.01 – 0.1), 0.623 | 1.4 ± 0.2 | 1.4 ± 0.2 | 0.0 (-0.1 – 0.1), 0.627 | 0.0 (-0.1 – 0.1), 0.618 |

**Table 8** Between-limb and between-group differences in temporospatial gait parameters at final follow-up

*differences between treatment groups in the side-to-side difference between limbs

| Outcome measures | Total (n=30) | | | Operative (n=10) | | | Non-operative (n=20) | | | Between-groups* |
|---|---|---|---|---|---|---|---|---|---|---|
| | *Involved* | *Uninvolved* | *Difference (95% CI), p value* | *Involved* | *Uninvolved* | *Difference (95% CI), p value* | *Involved* | *Uninvolved* | *Difference (95% CI), p value* | *Difference (95% CI), p value* |
| Step length, cm | 64.0 ± 6.9 | 63.6 ± 6.5 | 0.4 (-1.0 – 1.8), 0.595 | 62.0 ± 7.0 | 62.1 ± 6.3 | -0.1 (-1.9 – 1.6), 0.871 | 65.1 ± 6.8 | 64.4 ± 6.7 | 0.7 (-1.4 – 2.8), 0.352 | 1.0 (-2.0 – 4.1), 0.502 |
| Stride length, cm | 127.5 ± 13.1 | 128.0 ± 12.9 | -0.5 (-1.2 – 0.3), 0.213 | 124.4 ± 13.5 | 124.3 ± 12.4 | 0.0 (-1.3 – 1.3), 0.962 | 129.4 ± 12.9 | 130.1± 13.0 | -0.7 (-1.7 – 0.2), 0.879 | 0.5 (-1.0 – 2.1), 0.479 |
| Total support time, % gait cycle | 63.6 ± 1.6 | 63.4 ± 1.8 | 0.1 (-0.5 – 0.7), 0.682 | 64.2 ± 1.7 | 64.2 ± 1.5 | 0.0 (-1 – 1), 0.995 | 63.2 ± 1.5 | 63.0 ± 1.8 | 0.2 (-0.6 – 1.0), 0.52 | 0.0 (-1.2 – 1.3), 0.944 |

*Plantar- and dorsiflexion isokinetic strength*

The results describing plantar- and dorsiflexion isokinetic strength are reported in Table 9. In the total sample, the involved limb produced statistically significantly more dorsiflexion torque at 30°/s and statistically significantly less plantarflexion torque at 240°/s than the uninvolved limb. In the operative group, the involved limb produced statistically significantly more dorsiflexion torque at 30°/s and statistically significantly less plantarflexion torque at 240°/s. In the non-operative group, the involved limb produced statistically significantly less plantarflexion torque at 240°/s. The SRM describing the size of the differences ranged from 0.02 to 0.91. Between groups, there was a smaller side-to-side difference in dorsiflexion torque at 60°/s in the non-operative group (ES=0.86). The ES describing the size of the difference between treatment groups plantar- and dorsiflexion isokinetic strength ranged from 0.02 to 0.86.

When the involved limb present study values were compared to initial study values, there was a statistically significant main effect for time for plantarflexion torque at 60°/s and 240°/s (Figure 37 and Figure 41, respectively). There were no other statistically significant main effects or time by group interactions (Figure 33, Figure 34, Figure 35, Figure 36, Figure 38, Figure 39, Figure 40, Figure 42, Figure 43, Figure 44).

**Table 9** Between-limb and between-group comparisons of isokinetic strength at final follow-up

*differences between treatment groups in the side-to-side difference between limbs

| Outcome measures | Total (n=31) | | | Operative (n=12) | | | Non-operative (n=19) | | | Between-group* |
|---|---|---|---|---|---|---|---|---|---|---|
| | *Involved* | *Uninvolved* | *Difference (95% CI), p value* | *Involved* | *Uninvolved* | *Difference (95% CI), p value* | *Involved* | *Uninvolved* | *Difference (95% CI), p value* | *Difference (95% CI), p value* |
| Plantarflexion 30°/s, Nm | 63.4 ± 26.1 | 62.3 ± 25.4 | 1.1 (-4.8 - 7.0), 0.700 | 62.5 ± 31.5 | 62.2 ± 33.0 | 0.4 (-9.9 – 10.7), 0.935 | 63.9 ± 23.0 | 62.3 ± 20.3 | 1.6 (-6.3 - 9.5), 0.678 | 1.2 (-13.5 – 11.1), 0.844 |
| Dorsiflexion 30°/s, Nm | 26.8 ± 11.8 | 23.9 ± 10.5 | 2.9 (0.1 - 5.7), **0.044** | 26.7 ± 10.4 | 21.0 ± 10.9 | 5.7 (0.9 – 10.5), **0.024** | 26.9 ± 12.9 | 25.8 ± 10.0 | 1.1 (-2.4 - 4.6), 0.526 | 4.6 (-0.9 – 10.1), 0.099 |
| Plantarflexion 60°/s, Nm | 55.9 ± 24.3 | 58.2 ± 23.5 | -2.4 (-8.0 - 3.2), 0.388 | 52.8 ± 28.4 | 54.3 ± 30.6 | -1.5 (-14.6 – 11.7), 0.809 | 57.8 ± 22.0 | 60.8 ± 18.2 | -3.0 (-8.3 - 2.4), 0.259 | 1.5 (-10.2 – 13.1), 0.796 |
| Dorsiflexion 60°/s, Nm | 23.6 ± 12.3 | 22.3 ± 10.8 | 1.4 (-1.8 - 4.5), 0.390 | 23.5 ± 12.9 | 17.8 ± 8.5 | 5.7 (-0.04 – 11.4), 0.052 | 23.8 ± 12.3 | 25.2 ± 11.3 | -1.4 (-4.9 - 2.2), 0.424 | 7.1 (1.0 – 13.1), **0.024** |
| Plantarflexion 240°/s, Nm | 29.1 ± 13.8 | 35.0 ± 13.9 | -5.9 (-8.3 - -3.4), **<0.01** | 24.5 ± 11.5 | 30.8 ± 13.8 | -6.3 (-10.6 - -1.9), **0.009** | 32.0 ± 14.6 | 37.6 ± 13.7 | - 5.6 (-8.3 - -2.4), **0.002** | 0.7 (-4.4 – 5.8), 0.791 |
| Dorsiflexion 240°/s, Nm | 14.4 ± 8.4 | 15.1 ± 7.8 | -0.7 (-1.9 - 0.4), 0.205 | 12.6 ± 4.7 | 13.4 ± 6.7 | -0.8 (-3.3 – 1.7), 0.487 | 15.4 ± 10.0 | 16.1 ± 8.5 | -0.7 (-2.0 - 0.6), 0.286 | 0.1 (-2.3 – 2.5), 0.934 |

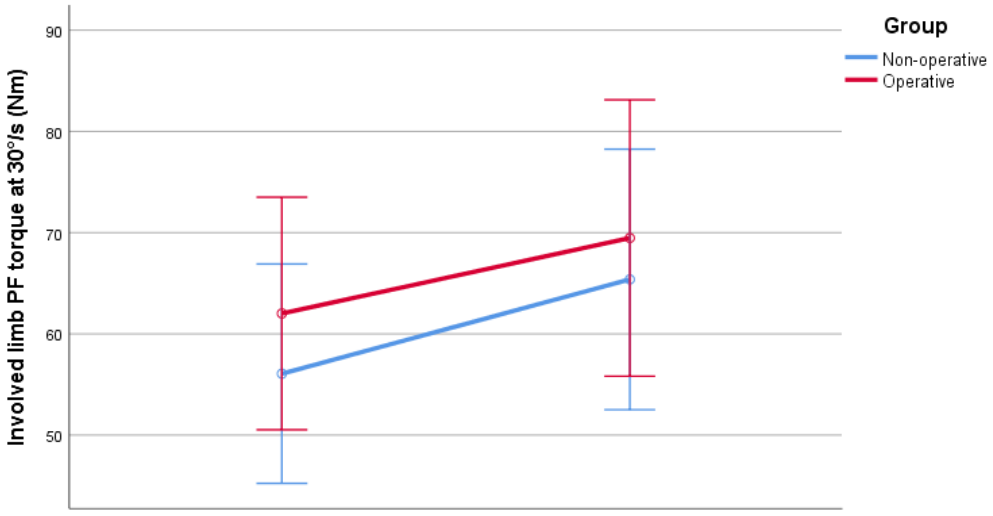


**Figure 33** Involved limb plantarflexion (PF) torque at 30°/s for the operative (n=16) and non-operative (n=18) groups at the initial follow-up (2 years) and final follow-up (>10 years) post-rupture

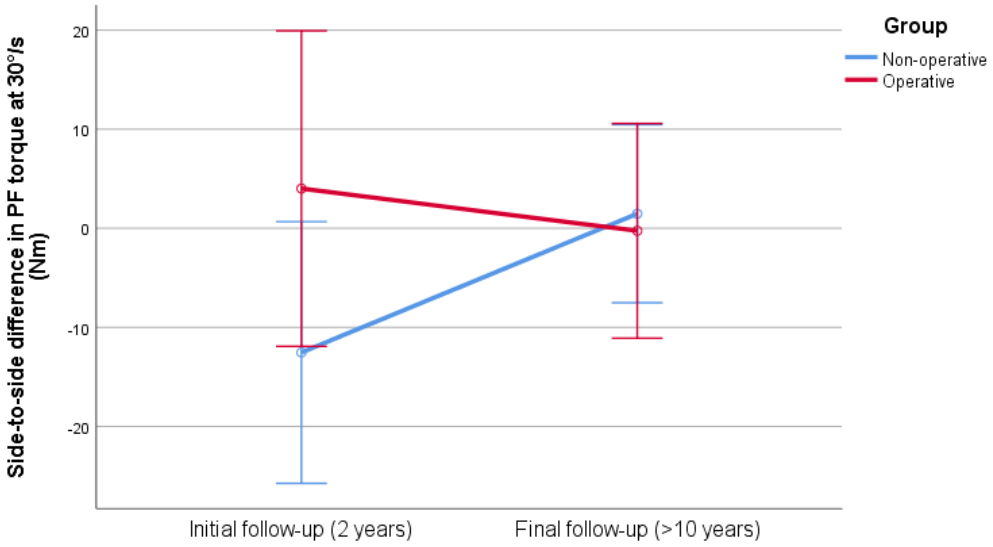


**Figure 34** Side-to-side differences in plantarflexion (PF) torque at 30°/s for the operative (n=11) and non-operative (n=16) groups at the initial follow-up (2 years) and final follow-up (>10 years) post-rupture

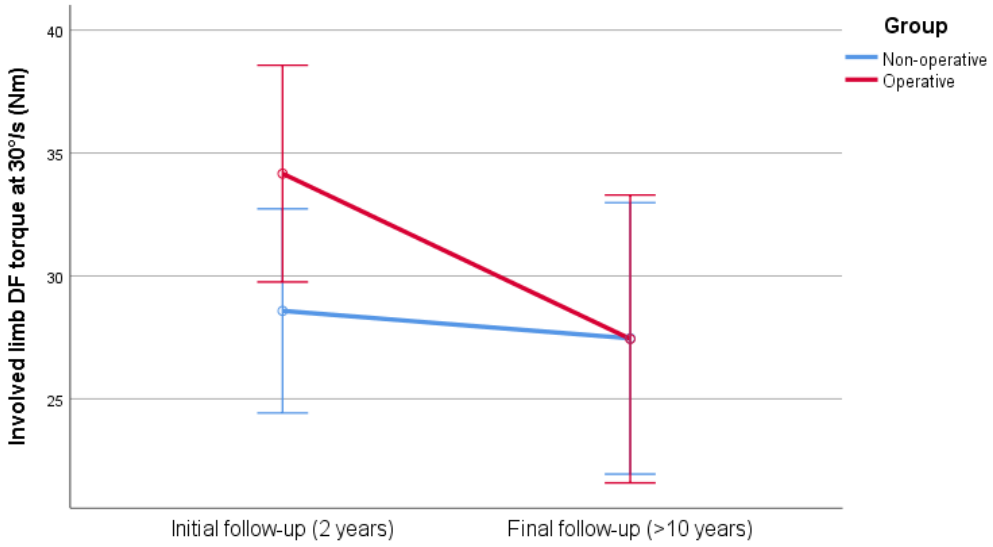


**Figure 35** Involved limb dorsiflexion (DF) torque at 30°/s for the operative (n=16) and non-operative (n=18) groups at the initial follow-up (2 years) and final follow-up (>10 years) post-rupture.

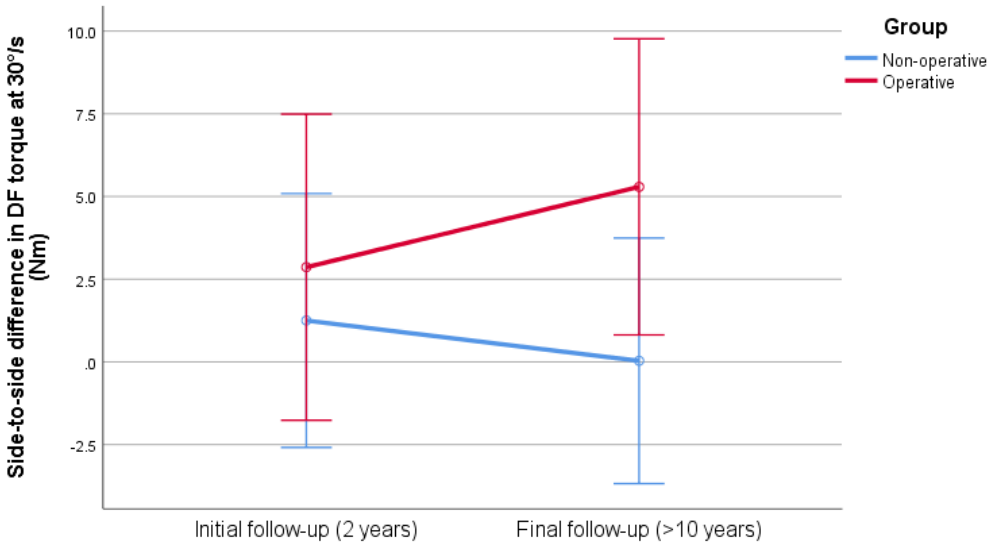


**Figure 36** Side-to-side differences in dorsiflexion (DF) torque at 30°/s for the operative (n=11) and non-operative (n=16) groups at the initial follow-up (2 years) and final follow-up (>10 years) post-rupture

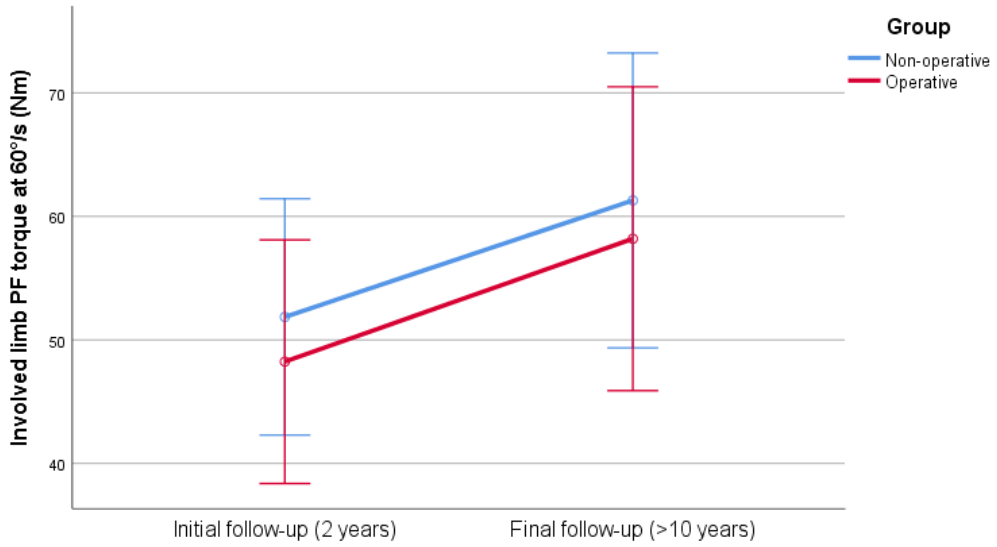


**Figure 37** Involved limb plantarflexion (PF) torque at 60°/s for the operative (n=16) and non-operative (n=17) groups at the initial follow-up (2 years) and final follow-up (>10 years) post-rupture

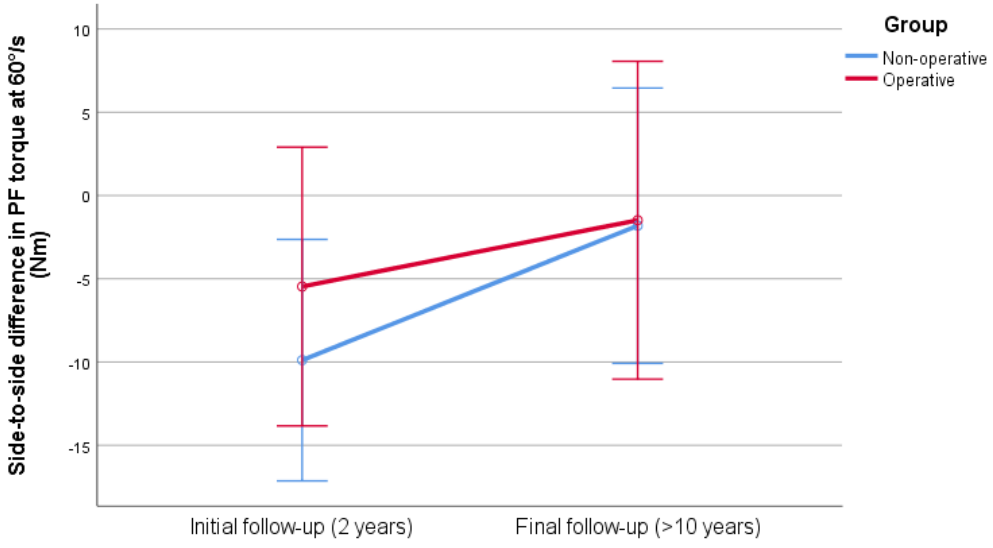


**Figure 38** Side-to-side differences in plantarflexion (PF) torque at 60°/s for the operative (n=12) and non-operative (n=16) groups at the initial follow-up (2 years) and final follow-up (>10 years) post-rupture

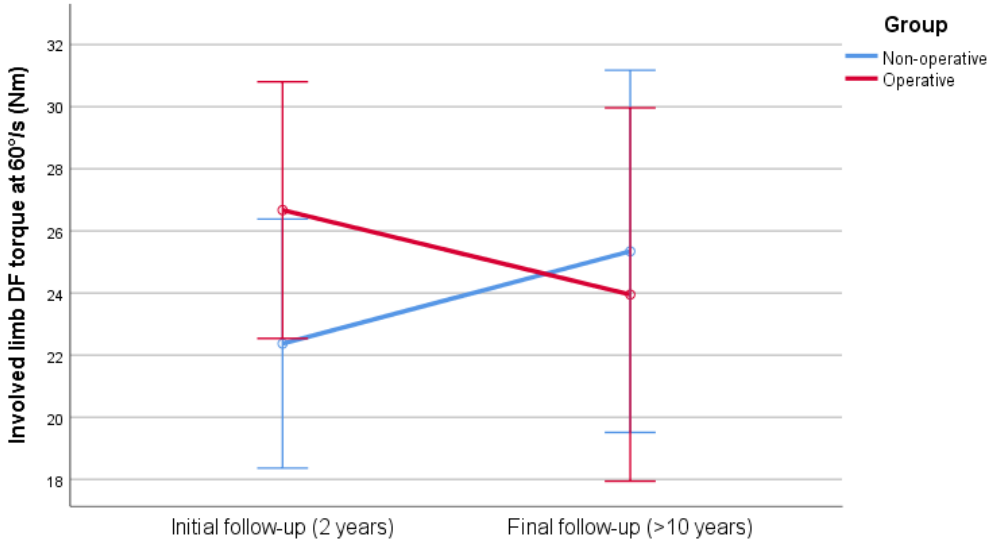


**Figure 39** Involved limb dorsiflexion (DF) torque at 60°/s for the operative (n=16) and non-operative (n=17) groups at the initial follow-up (2 years) and final follow-up (>10 years) post-rupture

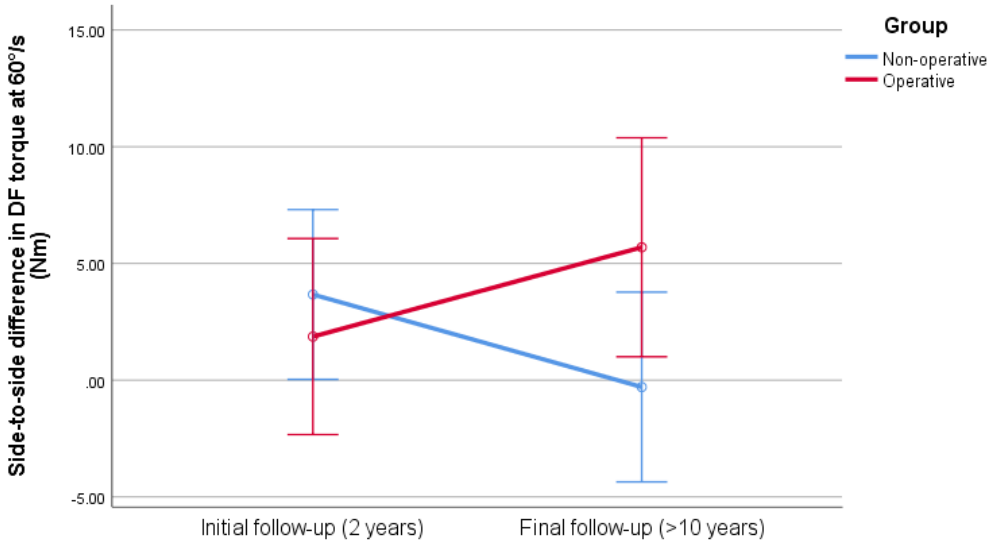


**Figure 40** Side-to-side differences in dorsiflexion (DF) torque at 60°/s for the operative (n=12) and non-operative (n=16) groups at the initial follow-up (2 years) and final follow-up (>10 years) post-rupture

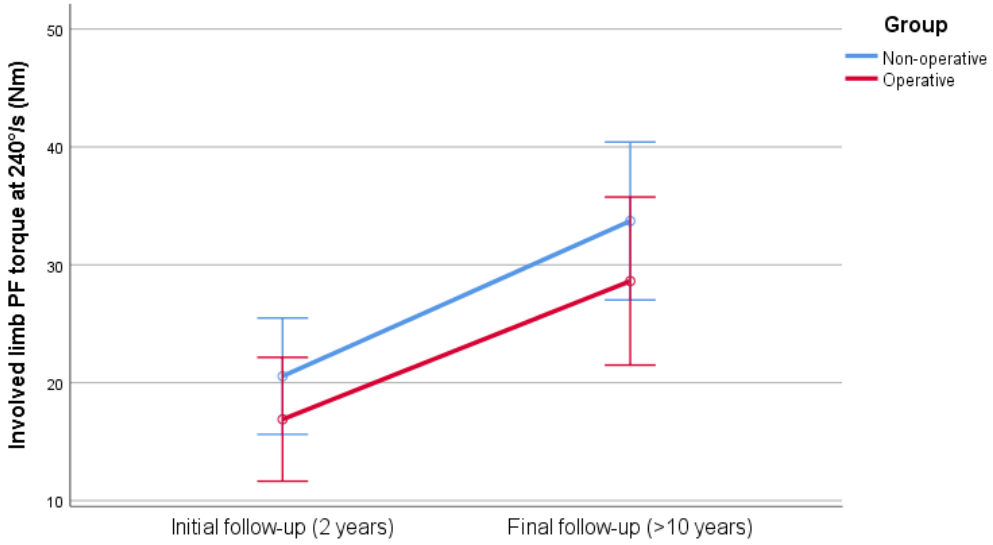


**Figure 41** Involved limb plantarflexion (PF) torque at 240°/s for the operative (n=15) and non-operative (n=17) groups at the initial follow-up (2 years) and final follow-up (>10 years) post-rupture

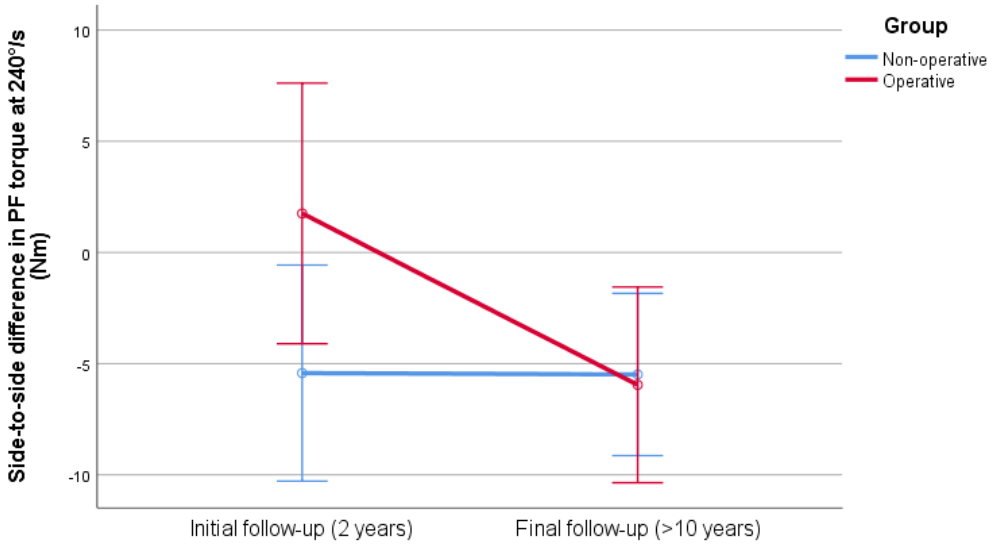


**Figure 42** Side-to-side differences in plantarflexion (PF) torque at 240°/s for the operative (n=11) and non-operative (n=16) groups at the initial follow-up (2 years) and final follow-up (>10 years) post-rupture

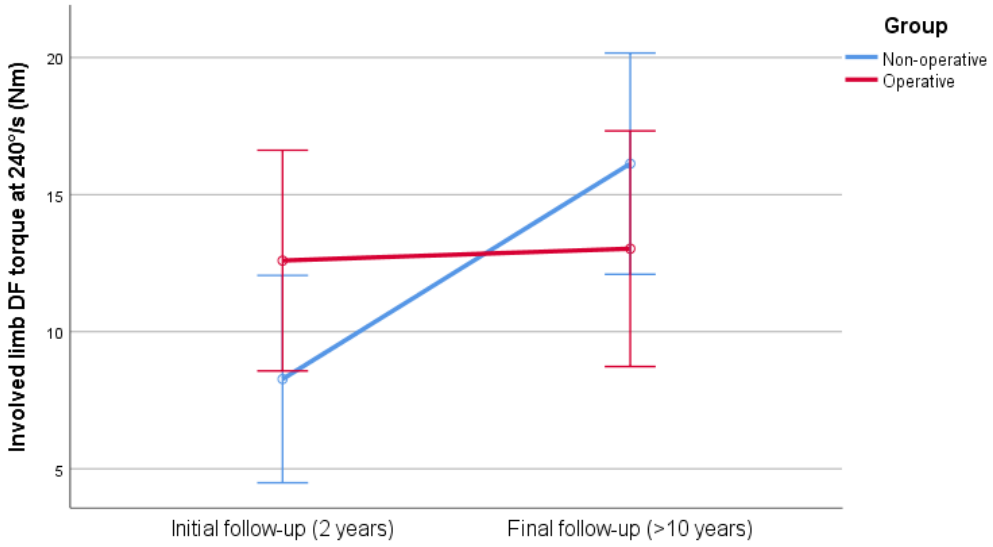


**Figure 43** Involved limb dorsiflexion (DF) torque at 240°/s for the operative (n=15) and non-operative (n=17) groups at the initial follow-up (2 years) and final follow-up (>10 years) post-rupture

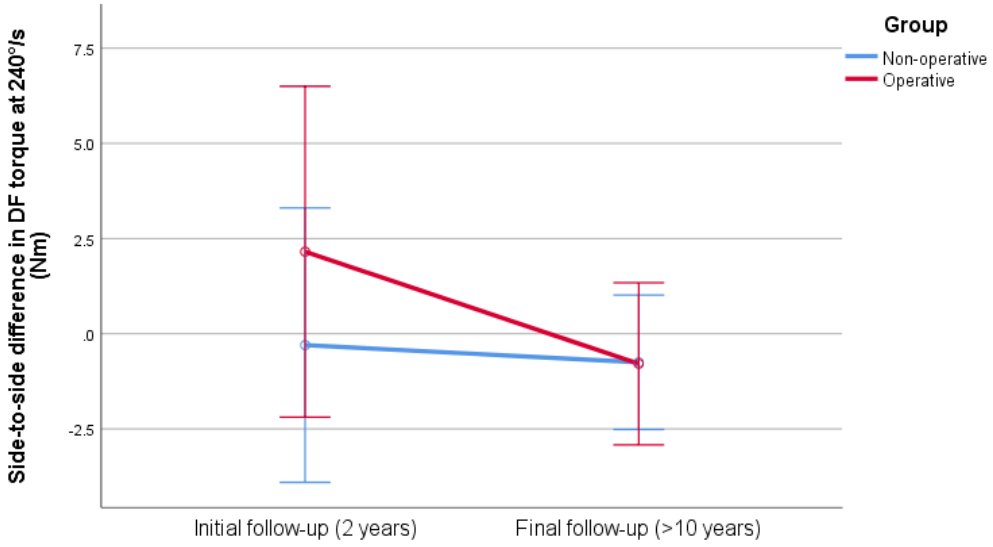


**Figure 44** Side-to-side differences in dorsiflexion (DF) torque at 240°/s for the operative (n=11) and non-operative (n=16) groups at the initial follow-up (2 years) and final follow-up (>10 years) post-rupture

### 5.3.4 Patient-reported outcome measures

*Achilles Tendon Total Rupture Score*

The ATRS favoured the non-operative group (Table 10). The ES describing the size of the difference between treatment groups was 0.62.

**Table 10** Between-group comparison of Achilles Tendon Total Rupture Score at final follow-up
*Abbreviations:* ATRS = Achilles Tendon Total Rupture Score

| Outcome | Total (n=43) | Operative (n=20) | Non-operative (n=23) | Difference (95% CI), p value |
|---|---|---|---|---|
| ATRS, out of 100 | 88.9 ± 15.2 | 84.1 ± 16.5 | 93.2 ± 12.8 | 9.1 (0.1 – 18.2), **0.048** |

*Leppilahti score*

The results describing the Leppilahti score in the final follow-up are reported in Table 11. The ES describing the size of the difference between treatment groups was 0.03. When the present study values were compared to the initial study values, the ANOVA indicated no statistically significant main effect for time (p=0.392), a statistically significant main effect for group (p=0.040), and no statistically significant time by group interaction (p=0.959) (Figure 45).

**Table 11** Between-group comparison of the Leppilahti score at final follow-up

| Outcome | Total (n=31) | Operative (n=12) | Non-operative (n=19) | Difference (95% CI), p value |
|---|---|---|---|---|
| Leppilahti score, out of 100 | 76.1 ± 15.2 | 75.8 ± 11.0 | 76.3 ± 17.6 | 0.5 (-11.2 – 12.1), 0.933 |

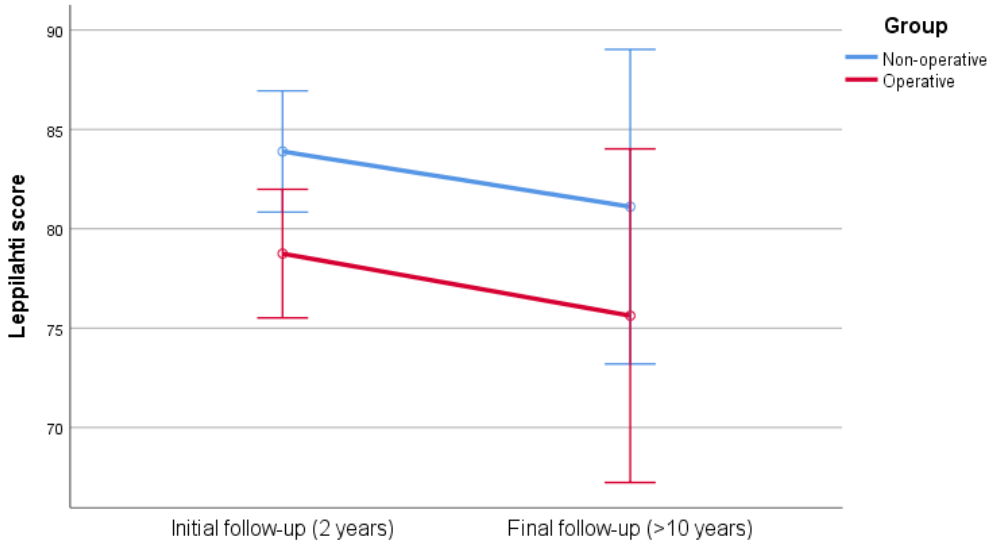


**Figure 45** Leppilahti scores for the operative (n=8) and non-operative (n=9) groups at the initial follow-up (2 years) and final follow-up (>10 years) post-rupture

### 5.3.5 Post hoc correlation analysis

There were several low to moderate correlations between the involved limb MRI and performance-based outcome measures. Specifically, there was a positive correlation between MAD and plantarflexion isokinetic strength at 30°/s (r=0.51, n=32, p=0.003), 60°/s (r=0.51, n=32, p=0.003), and 240°/s (r=0.35, n=32, p=0.049), and dorsiflexion isokinetic strength at 30°/s (r=0.42, n=32, p=0.016) and 60°/s (r=0.46, n=32, p=0.008).

Maximum calf circumference measured on MRI was positively correlated with plantarflexion isokinetic torque at 240°/s (r=0.349, n=32, p=0.05) and dorsiflexion isokinetic torque at 60°/s (r=0.449, n=32, p=0.01) and 240°/s (r=0.530, n=32, p=0.002). In contrast, maximum calf circumference was negatively correlated with peak plantarflexion moment during gait (r=-0.38, n=32, p=0.034).

The strongest association was between triceps surae CSA and isokinetic strength. There were statistically significant correlations ranging from r=0.36 to r=0.62 between all three muscle CSAs and plantar- and dorsiflexion isokinetic strength at 30°/s and 60°/s. Plantar- and dorsiflexion strength at 240°/s was correlated with gastrocnemius medialis CSA (plantarflexion, r=0.36, n=32, p=0.040; dorsiflexion, r=0.48, n=32, p=0.006) and soleus CSA (plantarflexion, r=0.65, n=32, p<0.01; dorsiflexion, r=0.665, n=32, p<0.01). Further, maximum one-legged jump height was positively correlated with gastrocnemius medialis (r=0.34, n=31, p=0.043) and soleus CSA (r=0.38, n=31, p=0.036). Finally, gastrocnemius medialis CSA was significantly correlated with excursion during gait (r=0.44, n=32, p=0.013).

# Chapter 6

# 6 Discussion

The primary purpose of this study was to investigate long-term outcomes after AATR treated operatively and non-operatively. The present results suggest that the involved limb does not return to the status of the contralateral limb at a mean of 15 years after injury, although there is considerable variability among outcome measures. The secondary objective was to describe changes from 2 to >10 years after AATR. Over time, the involved limb experienced decreased active plantar- and dorsiflexion range of motion and increased plantarflexion torque at 60°/s and 240°/s. The tertiary objective was to compare operatively and non-operatively treated patients. Four outcomes favoured non-operative treatment: AT MAD, dorsiflexion torque at 60°/s, the ATRS, and the Leppilahti score. No measures suggested better long-term outcomes for operatively treated patients.

*MRI outcome measures*

In the present study, the MAD of the AT was sometimes more than two times larger in the involved compared to the uninvolved limb. Using ultrasound, Bleakney et al. (2002) reported a MAD of 11.7 mm in the involved limb versus 5.4 mm in the uninvolved limb in a mixed cohort of patients treated conservatively, percutaneously, and with open surgery who were on average 63 months post-rupture. Similarly, Hufner et al. (2006) used ultrasound to evaluate the ATs of non-operatively treated patients at a mean of 5.5 years post-AATR and reported a mean tendon diameter of 9.5 mm, compared to 6.5 mm in the uninvolved tendon. Gigante et al. (2008) also reported larger anteroposterior diameters of the involved AT 12-months post-AATR in patients treated with both open and percutaneous surgery; however, the difference between limbs was not statistically significant. Our findings are consistent with those of Gigante et al. (2008) in that operatively treated participants had a larger AT anteroposterior diameter in their involved limb. Our data suggest substantially larger AT diameter in the involved limb 15 years later, and statistically significant differences between treatments groups with slightly larger side-to-side differences in patients treated operatively. However, the difference

between groups was 2.2 mm and it is unclear how much asymmetry is clinically meaningful.

Coupled with an increased MAD, the AT CSA was larger in the involved compared to the uninvolved limb, and diffuse thickening was noted throughout the tendon. Thickening of a tendon is consistent with tendinosis, a degenerative, non-inflammatory process that can decrease the strength of the tissue. Due to its associated pathological processes, it has been previously hypothesized that tendinosis can lead to rupture as a result of micro-tears within the weakened tendon (Arner & Lindholm, 1959; Barfred, 1973; Józsa & Kannus, 1997). However, although the involved AT was thicker compared to the uninvolved AT in this sample, only two participants in the present study had sustained a re-rupture since the initial trial. Both of these events occurred during the first 3 months following the initial rupture, a period within the healing process where tendon quality is reduced and the tissue is in a vulnerable state (Wu, Nerlich, & Docheva, 2017). Thus, there is no evidence in this sample that the presence of tendinosis at the mean of 15 years post-AATR is associated with re-rupture. Conversely, it is well accepted that degenerative changes and thickening in the tendon are related to the normal ageing process and will be present in all individuals to some degree (Koivunen-Niemelä & Parkkola, 1995; Pierre-Jerome, Moncayo, & Terk, 2010). The 'normal' contralateral tendon MAD in this sample was 7.2±1.6 mm. Koivunen-Niemelä & Parkkola (1995) reported an AT anteroposterior diameter of 6.7±1.0 mm in adults over 30 years old, compared with 6.3±0.5 mm in individuals 18-29 years old. Given that the average age in the present study is 58 old years, our results are similar to those of Koivunen-Niemelä & Parkkola (1995). The slightly larger MAD in the present study may be attributed to the fact that we measured maximum anteroposterior diameter, whereas Koivunen-Niemelä & Parkkola (1995) measured diameter at the level of the medial malleolus.

The stress imposed on a tendon during a task can be defined as the force transmitted to the tendon divided by its CSA. According to the mechanical theory of AATR, ruptures occur when the tissue is subjected to forces higher than it can physiologically tolerate (i.e. beyond ultimate strength). Thus, it may be advantageous to augment AT thickness to reduce stress at a given load, increasing the tolerance of the tendon and allowing for

larger gains in triceps surae strength through muscle hypertrophy. Physical loading is known to induce hypertrophy of tendons in animals (Sommer, 1987; Woo et al., 1982). In humans, thicker ATs are observed in active individuals who repeatedly expose their tendons to large loads (i.e. habitual runners), compared to inactive controls in younger and older populations (Kallinen & Suominen, 1994; Magnusson & Kjaer, 2003; Rosager et al., 2002). Post hoc analyses in the present study suggest MAD is positively correlated to plantarflexion isokinetic strength. Although the size of these correlations ($r=0.35$ to $0.509$, $n=32$, $p=0.003$ to $0.049$) suggest that strength is not wholly dependent on MRI measures of AT thickness, the associations may suggest that patients after AATR should focus on calf muscle strength training in their recovery to induce protective hypertrophic changes in the AT. Similarly, AT thickening seen on imaging should not necessarily be considered a deleterious outcome post-AATR.

Tendon elongation alters the relation between the AT and triceps surae muscle complex, and is a frequent complication post-AATR. Previous investigators have directly measured AT length using ultrasound, x-ray, and stereo-radiography, and indirectly measured it using increased dorsiflexion as a surrogate measure (Costa et al., 2006; Jacobs et al., 1978; Kangas et al., 2007; Nyström & Holmlund, 1983; Schepull, Kvist, & Aspenberg, 2012; Selvik, 1990; Silbernagel, Steele, & Manal, 2012; Young, Kumta, & Maffulli, 2005). We used a MRI approach previously described by Heikkinen et al. (2017) to define AT length as the distance from the distal soleus myotendinous junction to the posterior superior margin of the calcaneal tuberosity. It has been previously suggested that original anatomical AT length can only be restored post-AATR through surgical re-approximation of the tendon stumps, and avoidance of AT lengthening cannot be achieved with non-operative treatment (Maffulli, 1999). However, our MRI-defined results are consistent with those of Rosso et al. (2013) who found the AT to be longer in the involved compared to the uninvolved limb, and reported no differences in AT length between patients treated with open repair, a percutaneous surgical technique, and with non-operative care. In contrast, at study by Heikkinen et al. (2017) reported mean AT length of $68.8\pm3.0$ mm for treated surgically and $87.9\pm4.3$ mm for patients treated non-surgically, and this difference was statistically significant. However, the uninvolved limb was not imaged, therefore Heikkinen et al. (2017) was unable to evaluate the actual

tendon length in the healthy limb. The lack of difference between operative and non-operative groups in our investigation may be attributed to the fact that all patients were prescribed an identical accelerated functional rehabilitation protocol, a program that encourages controlled early weight-bearing and range of motion. Kangas et al. (2007) reported less severe AT elongation in patients who underwent a post-operative regimen that included early mobilization compared to patients whose ankles were initially immobilized during the early part of their recovery. Regardless of treatment, this study suggests that tendon elongation is a long-term observation in patients that sustain an AATR that current treatments and rehabilitation protocols do not fully ameliorate. Further, undergoing an accelerated functional rehabilitation protocol is an important factor to attain similar results in both operative and non-operative treated patients.

Calf circumference is commonly used to evaluate muscle trophic modifications and can be easily measured in a clinical setting using a measuring tape. Both the initial and present study measured calf circumference in this way at a distance of 15 cm inferior to the pole of the patella. In the present study, calf circumference of the involved limb was statistically significantly reduced compared to the uninvolved in the total pooled sample and both treatment groups. This finding is consistent with other mid to long-term studies ranging from 36 months to 12.6 years post-rupture following a range of surgical procedures and non-operative protocols (Bevoni et al., 2014; Horstmann et al., 2012; Hufner et al., 2006; Krueger-Franke, Siebert, & Scherzer, 1995; Mavrodontidis et al., 2015). Further, calf circumference in the present study did not change significantly from 2-years post-rupture to final follow-up. Thus, we suggest that decreased plantarflexor bulk after AATR and subsequent operative or non-operative treatment and accelerated functional rehabilitation cannot be fully recovered after this type of injury.

The present study also used an MRI-defined method to evaluate calf circumference. Though calf circumference measured clinically during a physical exam is commonly used in the AATR literature as a surrogate for lower limb muscle volume, they do not consider other influences such as body composition (i.e. presence of fat tissue) and swelling (Häggmark & Eriksson, 1979; Spennacchio et al., 2016). Therefore, we also evaluated calf muscle CSA using MRI since imaging can provide a better and more reliable

measurement of muscle size compared to calf circumference (Häggmark & Eriksson, 1979). At 15 cm below the inferior pole of the patella, there were statistically significant side-to-side differences in MRI-defined calf circumference in the total pooled sample and in the non-operative group when analyzed separately. Although a statistically significant difference did not appear in the operative group, it approached statistical significance ($p=0.051$). We also report statistically significant reductions in all triceps surae CSA in the involved compared to the uninvolved limb at this location. Given the similar findings between the clinical and imaging-based measures at 15 cm distal to the inferior pole of the patella, we suggest that using a measuring tape is an appropriate, low cost method to measure calf circumference at this location in order to make inferences regarding lower leg muscle morphology in this population.

While standardization of calf circumference measurement (i.e. in the same location on both limbs in all patients) is popular in the literature (Horstmann et al., 2012; Hufner et al., 2006; Krueger, Siebert, & Scherzer, 1995), depending on where the AT tear occurred and due to between subject variability, vastly different morphological changes between limbs can result. Thus, a more appropriate measure may be the maximum calf circumference of each limb. Interestingly, at the level of maximum muscle bulk, we did not find significant calf circumference side-to-side differences in the operative group. Unlike the clinical measure in the operatively treated participants, there was no approach toward significance in calf circumference at maximum muscle bulk. Upon closer examination, these results can be explained by examining triceps surae CSA - gastrocnemius lateralis CSA was not statistically different between limbs at maximum muscle bulk in the operative group. It is difficult to interpret why gastrocneumius lateralis specifically was different to gastrocnemius medialis and soleus. Häggmark and Eriksson (1979) investigated the structural and morphologic changes in calf muscles during six weeks of immobilization following surgery for AATR using muscle biopsies and computed tomography. The combined CSA of the gastrocnemius and soleus muscles was reduced by 23% in the involved compared to the uninvolved limb. Further, measurement of the muscle fibre area of a histochemically stained section showed a reduction in CSA of the soleus (type 1) muscle fibres and an increase in the gastrocnemius (type 2) fibres, though the latter change was not statistically significant. However, it is unclear which

head of the gastrocnemius these conclusions were drawn from. The differences in our results compared to those of Häggmark and Eriksson (1979) could be attributed to the fact we conducted a much longer-term study. It is possible that changes in type 1 and type 2 muscle fibres and CSA occur at different stages in recovery. Further, the patients in our study underwent a post-rupture accelerated functional rehabilitation protocol, which has been shown to decrease muscle atrophy when compared to early immobilization (Zhou et al., 2017). Studies by Booth and Kelso (1973) and Thomason and Booth (1990) showed that type 1 fibres were more vulnerable to atrophy from immobilization than type 2 fibres. Given that the soleus only crosses the ankle joint whereas the gastrocnemius crosses both the knee and ankle joints, the soleus cannot produce contract to produce work when the ankle is immobilized (Heikken et al., 2017). Reduced movement in the soleus compared to the gastrocnemius may explain why there were side-to-side differences in the soleus in the present study, but does not clarify why gastrocnemius medialis appears to be more affected compared to gastrocnemius lateralis.

Although our results suggest that MRI is able to provide more information concerning muscle trophic modifications by examining individual muscle CSA than a more global measure of calf circumference, MRI may not be a cost-effective instrument to use clinically in this respect. However, it is a useful research tool to identify changes in specific muscles after AATR. Further, this study suggests that clinical calf circumference measurements should be interpreted with caution when making decisions regarding an individual's muscle CSA and quality, and locations on the lower leg where the measurement is taken should be considered carefully.

*Performance-based outcome measures*

Several studies have used dynamometers to measure strength following AATR. There is, however, no consensus regarding the best method to determine lower leg strength (Bevoni et al., 2014; Hohendorff et al., 2008; Horstmann et al., 2012; Josey et al., 2003; Krueger-Franke, Siebert, & Scherzer, 1995; Lantto et al., 2015; Mavrodontidis et al., 2015; Spennacchio et al., 2016; Willits et al., 2010). Further, strength measures have been difficult to interpret and compare between studies due to inconsistencies in the test

position, type of limb stabilization, angular velocity evaluated, and the type of isokinetic device used (Möller et al., 2005). Due to this high degree of variability and lack of standardization, several systematic reviews have struggled to conduct meta-analyses on strength outcomes (Jiang et al., 2012; Ochen et al., 2018; Wilkins & Bisson, 2012). The present study chose the isokinetic strength protocol included in the Leppilahti score, the first reported disease-specific standardized protocol for evaluation of outcome after AT rupture (Leppilahti et al., 1998). The Leppilahti score is reported in many studies and was used in the initial trial from which the present study recruited participants (Bevoni et al., 2014; Kaniki et al., 2014; Lantto et al., 2015; Willits et al., 2010). Higher plantarflexion torques at 60°/s and 240°/s in the involved limb were identified in the present study compared to the initial study. However, this improvement should be interpreted with caution as no side-to-side differences were evident between these time points. We report higher dorsiflexion torques at 30°/s in the involved compared to the uninvolved limb in the total pooled sample and in the operative group. Leppilahti et al. (2000) reported dorsiflexion torque at 30°/s was 4% higher in the involved compared to the uninvolved limb in patients 3.1 years post-surgical repair for AATR, though the difference between limbs was not significant. We identified a larger side-to-side difference in dorsiflexion torque at 60°/s in the operative group compared to the non-operative group. However, the involved limb in the operative group produced more torque than the uninvolved, and the opposite was true for the non-operative group. Long-term results in previous studies are also inconsistent at this angular velocity. Horstmann et al. (2012) reported reduced torques in both plantar- and dorsiflexion in the involved compared to the uninvolved limb at a mean of 11 years post-surgical repair for AATR. In contrast, Bevoni et al. (2014) showed no difference between the involved and uninvolved limbs at 36 months post-AATR in patients treated surgically. Leppilahti et al. (2000) reported a 0.1% deficit in the involved compared to the uninvolved limb in dorsiflexion torque at 60°/s at 3.1 years post-surgery, and this difference was not significant. Further, in patients 4.6 years following open surgical repair, Bradley and Tibone (1990) reported that the involved limb achieved 82% and 108% of the contralateral limb's plantarflexion and dorsiflexion torque at 60°/s, respectively. Due to lack of concise reporting, it is unclear if the difference between limbs was statistically significant. At the final angular velocity,

participants in the present study showed diminished plantarflexion torque at 240°/s in their involved versus uninvolved limb. Similarly, Leppilahti et al. (2000) reported a 2% deficit in plantarflexion torque at 240°/s at 3.1 years post-injury, and this difference between limbs was significant. In the initial study at the two year follow-up, there was a small statistically significant difference between groups in plantarflexion torque at 240°/s in favour of the operative group; however, there were no such differences in the present study (Willits et al., 2010) which suggests delayed recovery in the non-operative group compared to the operative.

Although we used a previously described isokinetic strength protocol (Leppilahti et al., 1998), given the lack of studies that have reported raw data from this section of the Leppilahti score, we agree that strength measurements in this population are challenging to compile. Therefore, we recommend future studies report the overall Leppilahti score and the isokinetic evaluation separately in order to make meaningful comparisons.

Previous investigators have reported significant correlations between muscle strength and CSA (Ikai & Fukunaga, 1968; Maughan, Watson, & Weir, 1984). The present results emphasize muscle CSA is not the sole factor in determining strength. Our post hoc analyses suggest several positive correlations between triceps surae CSA and plantarflexion isokinetic strength. The size of these associations (i.e. $r^2$) varies considerably, suggesting the amount of variance in strength that can be explained by its association with CSA could be as low as 13% or as high as 44%. Horstmann et al. (2012) suggested factors other than muscle size may play a role in generating torques comparable to those of the uninvolved limb, and postulated that tendon length influences the capacity to produce force at a given ankle angle. Suydam et al. (2015) reported increased AT length and calf muscle activation during walking in the involved limb of surgically treated patients at 12 months post-AATR. The authors suggested functional deficits are primarily due to anatomical changes in AT rather than neural inhibition to the muscle, and that greater muscle activation could be a compensatory mechanism for increased AT slack. As the present study identified both AT lengthening and decreased muscle bulk (though not statistically significantly correlated), increased calf muscle activation could explain why the side-to-side differences in strength tests were not as

robust (i.e. statistically significant) in this sample. Further, Manegold et al. (2019) suggested that muscular atrophy in the triceps surae could lead to compensatory hypertrophy of the deep flexors (e.g. flexor digitorum longus or flexor hallucis longus) in order to aid in plantarflexion to produce similar side-to-side strength. Future studies should evaluate the CSA and activation of muscles in other compartments of the lower leg in this population. Interestingly, the highest correlations in the present study are between soleus CSA and plantarflexion isokinetic strength. This finding may help guide the prescription of specialized exercises during rehabilitation to target the soleus. For example, heel-rises are a fundamental item in AATR rehabilitation, and can be performed with either a straight or slightly bent knee. The latter configuration challenges the soleus to a greater extent than the straight leg heel-rise, since the soleus a single joint that only plantarflexes the ankle whereas the gastrocnemius is a two joint muscle that is unable to generate as much power when the knee is flexed. Through placing greater importance on training the soleus, AATR patients could experience greater gains in plantarflexion strength.

Short-term studies determine overall outcome post-AATR using measures such as re-rupture rate, complications, the time required to return to full activity, and patient satisfaction. However, re-rupture rates post-AATR are present yet fairly low, though a number of studies have reported patients fail to achieve full function in spite of good results in terms of overall outcome and satisfaction (Don et al., 2007). In more recent studies, there has been a proposed shift from using re-rupture rate as the primary outcome toward restored function with minimal symptoms as the primary goal of AATR treatment (Bergkvist et al., 2012; Nilsson-Helander et al., 2010; Olsson et al., 2013; Suchak et al., 2008). This is especially important in long-term studies as most patients have returned to some form of sports or recreational activity at 1 year post-rupture, and it is expected that functional performance should be improved compared to the first year or two of recovery (Brorsson et al., 2017). However, information regarding the long-term strength of the triceps surae and its influence on more demanding physical performance is limited (Tengman & Riad, 2013).

Jumping is an action that requires activation of the glutei, hamstrings, quadriceps, and lower leg musculature (Vanrenterghem et al., 2004). Though this task involves many variables, contribution of the AT and calf musculature contraction to take off and during landing is of great importance (Tengman & Riad, 2013). That is consistent with the present results suggesting greater triceps surae CSA is associated with higher maximum vertical jump height. The aim of a study by Quagliarella et al. (2010) was to propose a test to assess the restoration of functional capacity in order to augment clinical examination in patients who undergo surgical repair for AATR. A countermovement jump was chosen as it is the most common way to perform a standing vertical jump, and involves dynamic preloading in which accumulation of elastic energy by passive pre-stretching of muscle mass occurs. Quagliarella et al. (2010) evaluated patients who underwent open surgical repair at 24 months post-injury, and reported no significant differences in flight time between limbs. Although the present study did not evaluate flight time, vertical jump height can be derived from flight time and thus represents the same parameter. We did not find side-to-side differences in maximal countermovement vertical jump height in the operative group. Our results are not consistent with those of Nilsson-Helander et al. (2010) who found statistically significantly lower maximum jump height values for the injured compared to the uninjured limb. However, Nilsson-Helander et al. (2010) studied a drop countermovement jump in which participants start by standing on one leg on a 20 cm high box, then "fall" down to the floor, and directly upon landing, perform a maximum vertical single-legged jump. The addition of a "drop" requires absorption of high external loads during the landing phase, and made their protocol more demanding than the standard countermovement jump in the present study. As external load increases, the plantarflexors are challenged to a greater extent, and thus the drop countermovement jump may show greater asymmetry between limbs (Powell et al., 2018; Willy et al., 2017). However, Nilsson-Helander et al. (2010) evaluated patients after 12 months post-surgery, which may not have been enough time for patients to show marked recovery, unlike our long-term follow-up. Further, Nilsson-Helander reported no differences in jump performance between the operative and non-operative group, which is in agreement with the present study. However, our results are in contrast to a study by Olsson et al. (2013) that reported that between limb differences in drop countermovement

jump height at 12 months post-AATR favoured the operative group. Nilsson-Helander et al. (2010) hypothesized that it is possible that patients treated non-surgically require a longer recovery period. This hypothesis could explain why there were no differences between groups in the present study, as all participants had ample time for rehabilitation. However, we were limited by our sample size in detecting differences between groups, and statistically significant side-to-side differences were identified when the total sample was pooled. Thus, we suggest that residual functional impairment in the involved limb persists in patients following AATR during an explosive functional task. Based on the patients' expectations regarding return to sport, rehabilitation programs may need to emphasize re-training protocols that improve specific athletic movements so as to bring about a more complete functional recovery. For example, jumping and landing on a single limb may be important to basketball and volleyball players, while being comfortable pivoting may be more beneficial to squash and badminton players.

Given that the triceps surae is a combination of slow (soleus) and fast (gastrocnemius) twitch muscles, the calf muscles are able to produce repeated repetitions of low torque as well as high peak torques (Möller et al., 2005). Therefore, it is important to investigate both muscular endurance and strength to get a full picture of triceps surae function and how it pertains to activities of daily living and sports performance. The heel-rise test for muscular endurance is a recommended measure of functional recovery after AATR (Silbernagel et al., 2010; Spennacchio et al., 2016). The present study reported that participants could perform fewer heel-rise repetitions on the involved compared to the uninvolved limb in only the operative group. This is consistent with a study by Westin et al. (2018) who reported surgically treated patients at 51 months post-AATR re-rupture performed 29 heel rises on the involved limb compared to 32 on the uninvolved (MD = 3, 95% CI (1-5), p=0.004). The present study did not find a difference between limbs in the non-operative group. In contrast, Josey et al. (2003) reported a statistically significantly lower number of heel-rise repetitions on the involved compared to the uninvolved limb in patients treated non-operatively at an average of 55 months post-rupture. Given our inconsistent results in other outcomes such as calf muscle isokinetic strength, it is difficult to interpret why there were no side-to-side differences in heel-rise repetitions in the operative group but not the non-operative group. A study by Silbernagel et al. (2010)

used the same heel-rise testing protocol as the current study, with the exception that the authors attached a linear encoder (spring-loaded string connected to a sensor) to the heel of each participant's shoe while performing the task. Using this piece of equipment, Silbernagel et al. (2010) were able to calculate the total distance travelled by the participant across all of their repetitions. This distance was then multiplied by the participant's body weight to calculate "total work" in joules. At 12 months post-rupture, the patients had achieved a limb symmetry index (involved limb value divided by uninvolved limb value, then multiplied by 100) of 95% on the number of heel-rise repetitions parameter, but only a mean leg symmetry index of 76% on the work parameter. Thus, the authors suggested that calculating heel-rise work has good validity and even greater ability to detect differences between the involved and uninvolved limbs than a test that only measures the number of heel-rise repetitions in patients with AATR. Unfortunately, we did not have access to a linear encoder, and thus did not calculate total work. We suggest that future studies should consider using such an instrument as it may be able to offer more information regarding muscular endurance in the long-term post-AATR.

Recovery of independent walking is the first functional milestone that occurs in AATR rehabilitation (Agres et al., 2018). Given the major role of the triceps surae during gait, an intact and physiological musculoskeletal unit is necessary for forward propulsion (Anderson & Pandy, 2003; Manegold et al., 2019; Neptune, Kautz, & Zajac, 2001). Therefore, strength deficits involving lower push off force during walking can potentially cause long-term deviations in gait (Tengman & Riad, 2013). However, using 3-dimensional gait analysis, the present study did not identify any side-to-side or between group differences in plantar- and dorsiflexion angles and moments, or temporospatial gait parameters. In contrast, Don et al. (2007) reported higher dorsiflexion angles and lower step length in the involved compared to the uninvolved limb in AATR patients evaluated at 24 months post-surgical repair. In a medium term (average 4.5 years) follow-up of non-operative AATR patients, Speedtsberg et al. (2019) reported that the peak dorsiflexion angle in stance was 13.4% larger in the involved versus uninvolved limb. Similarly, Manegold et al. (2019) showed that maximum dorsiflexion angle was higher, and maximum plantarflexion angle and full angle sagittal range of motion were lower in

the involved compared to the uninvolved limb in AATR patients at an average of 43.5 months post percutaneous surgical repair. Finally, Tengman and Riad (2013) evaluated a mixed cohort of operative and non-operative AATR patients at an average of 3.3 years post-rupture and found the peak plantarflexion moment was lower on the involved side compared to the uninvolved. However, in agreement with the present study, Tengman & Riad (2013) reported no differences between limbs in step length or time spent in the stance phase. It is possible that the results of the present study differed from previous studies because of the long-term follow-up. For example, participants could have adapted to any alterations in ankle status that occurred post-AATR and this may have gradually influenced walking patterns in both the involved and uninvolved sides. Further, walking may not be a strenuous enough task to show robust differences between limbs. It may be worthwhile to investigate other more demanding cyclic activities, such as running, in this population.

*Physical examination outcome measures*

Measurement of sagittal plane ankle range of motion (both actively and passively) is common in both clinical and research settings post-AATR. Previous literature has hypothesized that increased dorsiflexion is an indirect measure of the length of the musculotendinous unit of the calf. A cadaveric study by Costa et al. (2006) aimed to investigate the relationship between AT lengthening and dorsiflexion at the ankle joint, and reported that maximal dorsiflexion was increased by a mean of 12° for each 10 mm increase in AT length. The authors proclaimed that the AT is the anatomical structure that limits dorsiflexion, and as such, dorsiflexion range of motion would appear to be a clinically useful indicator of tendon length. The present study found significantly decreased plantarflexion and increased dorsiflexion active and passive range of motion in the involved compared to the uninvolved limb in the total pooled sample and the non-operative group. Interestingly, no differences in either active or passive plantarflexion or dorsiflexion were present in the operative group, despite significant AT lengthening in the same group. Therefore, similar to previous studies, our results challenge the assumption that clinically measured dorsiflexion can be used as a surrogate for AT lengthening (Manegold et al., 2019; Rosso et al., 2013). Previous long-term

investigations have also reported widely inconsistent results regarding ankle range of motion post-AATR (Bevoni et al., 2014; Hohendorff et al., 2008; Horstmann et al., 2012; Josey et al., 2003; Krueger-Franke, Siebert, & Scherzer, 1995; Tengman & Riad, 2013; Westin et al., 2018). Of note, active plantarflexion range of motion in the involved limb decreased significantly from 2-years post-rupture to final follow-up, and similarly, the side-to-side difference also decreased. Active dorsiflexion range of motion in the involved limb decreased over time, while the side-to-side difference increased. As there was a large difference between the two-year time point and our average of 15-year follow-up, we are unsure when these changes occurred. It is possible that the AT is a key determinant of maximum dorsiflexion when the tendon is lengthened, though it is not clear at which point in recovery this may be true. If feasible, future studies should seek to follow-up with patients at more regular time points in order to identify when changes in tendon lengthening occur and their effect on ankle range of motion.

*Patient-reported outcome measures*

It is essential that imaging and biomechanical data be complemented with clinically relevant patient-reported outcomes to foster a comprehensive approach to healthcare. Due to its injury specific nature, the ATRS is currently the most appropriate patient-reported outcome measure for evaluating the acute management of AATR, and has also been used in long-term follow-up studies (Spennacchio et al., 2016). There was a significantly higher ATRS score in the non-operative compared to the operative group in the present study, although high scores in both groups indicate that the majority of participants had satisfactory outcomes. Our results are consistent with other mid to long-term studies that reported ATRS scores of 78.6 - 90.6 in non-operative patients at 3.3 to 7.6 years post-rupture, and scores of 81.7 – 90.5 in open surgery patients at 3.6 to 7.6 years post-rupture (Bergkvist et al., 2012; Lim, Lees, & Gwynne-Jones, 2017; Olsson et al., 2013; Rosso et al., 2013; Tengman & Riad, 2013; Westin et al., 2018). However, unlike the present study, there were no differences between groups in previous investigations that compared operative versus non-operative patients (Bergkvist et al., 2012; Olsson et al., 2013; Lim, Lees & Gwynne-Jones, 2017; Rosso et al., 2013). It has been previously stated that Nilsson-Helander et al. (2010) postulated that patients treated non-operatively require a

longer recovery period than those treated operatively. However, Tengman & Riad (2013) reported no relationship between ATRS score and time after injury in non-operatively treated patients at an average of 3.3 years post-rupture. Although previous long-term studies have reported similar results between groups, given that the present study is the longest-term follow-up, perhaps differences in patient-reported outcomes are more evident at this stage because of the long period of possible natural recovery and improvement. Regardless, we believe the ATRS is helpful in evaluating whether patients continue to improve over time or if their symptoms persist. While it is important to gather information regarding functional performance, it is also crucial to understand what is subjectively important to participants in their recovery.

The Leppilahti score combines both subjective assessments of symptoms and objective measures such as ankle range of motion and isokinetic calf strength (Leppilahti et al., 1998). Scores are arbitrarily categorized as excellent (90-100 points), good (75-85 points), fair (60-70 points), and poor (55 or less points). In a study by Bevoni et al. (2014), the mean Leppilahti score in patients 36 months post open surgery for AATR was 91.8 points. At 11 years post-rupture, Lantto et al. (2015) reported a mean score of 92.9 in patients who had been treated with open surgical repair and early mobilization. In the present study, the total pooled sample of participants had good (76.1 points) outcomes on average - a score considerably lower than the excellent results achieved in the two aforementioned studies. However, patients in the studies by Bevoni et al. (2015) and Lantto et al. (2015) were on average under 40 years old, compared to an average age of 57 years in the present study. Given that the Leppilahti score incorporates range of motion and strength measurements and these two attributes are known to decrease with age as tissues stiffen and muscle mass diminishes, the difference between studies could be due to an ageing effect. Interestingly, no significant effect for time was observed from the 2-year to final follow-up, although we observed a significant main effect for group, which favoured the non-operatively treated participants. As the aforementioned other long-term studies evaluated surgical patients only, we suggest that future investigations should confirm our results in non-operative patients with a larger sample size.

## 6.1 Study strengths

This study has the longest-term follow-up to date evaluating outcomes following AATR. Our evaluation was extremely comprehensive - one of the only studies to evaluate structural, clinical, functional, and patient-reported outcomes within a single study. Outcome assessors performing the follow-up measures and the radiologist who reviewed the MR images were blinded, thereby reducing performance and observational biases.

## 6.2 Study limitations

Selection bias is possible. Participants who did not have good outcomes may not have agreed to be followed-up. We aimed to overcome this limitation by contacting all potential participants in our sample and using participants from a previous randomized controlled trial. Further, given the relatively small number of patients who returned for testing, we had limited power to detect a small treatment effects. Also, due to this lower sample size, we did not have strict inclusion criteria for lower limb extremity impairments unrelated to the AT, and these other impairments could have influenced side-to-side differences between limbs. Another limitation is the potential for type I errors, given the many outcome measures investigated. However, while these results need confirmation in a larger cohort of patients, they provide useful information regarding the healing process in the AT and lower leg musculature following treatment for AATR.

## 6.3 Conclusion

This long-term follow-up suggests that side-to-side differences in a wide range of outcomes persist >10 years post-AATR. Several outcomes changed from 2-years post-injury to the final follow-up, though results were inconsistent. No outcomes favoured operative over non-operative treatment, although no general recommendation can be given regarding the optimal treatment for AATR given the small sample size. Future studies evaluating more participants are needed to further our knowledge in how the identified deficits can be minimized through improved treatment and rehabilitation.

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# Appendices

## Appendix A Fowler Kennedy Sports Medicine Clinic Achilles tendon rupture accelerated functional rehabilitation protocol

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### ACHILLES TENDON RUPTURE
### Accelerated Functional Rehabilitation Protocol

**0 – 2 WEEKS**

- Aircast boot with 2 cm heel lift
- NWB with crutches

**2 – 6 WEEKS**

- Aircast boot with 2 cm heel lift
- Protected weight-bearing with crutches as required
- Active plantar and dorsi flexion to neutral, inversion /eversion below neutral
- Modalities to control swelling
- Knee/ hip exercises as appropriate
- NWB fitness/cardio work
- Hydrotherapy (within motion and weight-bearing limitations)

**6 – 8 WEEKS**

- Aircast boot
- D/C heel lift
- WBAT
- Dorsiflexion stretching, slowly
- Graduated resistance exercises (OKC, CKC, functional)
- Proprioceptive and gait retraining
- Modalities as indicated
- Fitness/cardio to include WBAT
- Hydrotherapy

**8 – 12 WEEKS**

- Wean off boot
- Return to crutches/cane as necessary; then wean off
- Continue to progress ROM, strength, proprioception

**>12 WEEKS**

- Continue to progress ROM, strength, proprioception
- Retrain strength, power, endurance
- Increase dynamic WB exercise, include plyometric training
- Sport specific retaining

1

# Appendix B Ethics approval

Western Research

**Date:** 9 October 2018

**To:** Dr. Kevin R. Willits

**Project ID:** 111402

**Study Title:** Operative versus non-operative treatment of acute Achilles Tendon rupture: A >10 year follow-up

**Application Type:** HSREB Initial Application

**Review Type:** Delegated

**Full Board Reporting Date:** 16Oct2018

**Date Approval Issued:** 09/Oct/2018 09:26

**REB Approval Expiry Date:** 09/Oct/2019

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Dear Dr. Kevin R. Willits

The Western University Health Science Research Ethics Board (HSREB) has reviewed and approved the above mentioned study as described in the WREM application form, as of the HSREB Initial Approval Date noted above. This research study is to be conducted by the investigator noted above. All other required institutional approvals must also be obtained prior to the conduct of the study.

**Documents Approved:**

| Document Name | Document Type | Document Date | Document Version |
|---|---|---|---|
| 111402_ATRSV2_Aug13_C | Online Survey | 13/Aug/2018 | 2 |
| 111402_LeppilahtiV2_Aug13_C | Online Survey | 13/Aug/2018 | 2 |
| 111402_LOIV5_Sept26_C | Written Consent/Assent | 26/Sep/2018 | 5 |
| 111402_TelephoneScriptV2_Aug13_C | Telephone Script | 13/Aug/2018 | 2 |
| Data collection form | Other Data Collection Instruments | 30/May/2018 | 1 |
| Protocol | Protocol | 30/May/2018 | 1 |

No deviations from, or changes to, the protocol or WREM application should be initiated without prior written approval of an appropriate amendment from Western HSREB , except when necessary to eliminate immediate hazard(s) to study participants or when the change(s) involves only administrative or logistical aspects of the trial.

REB members involved in the research project do not participate in the review, discussion or decision.

The Western University HSREB operates in compliance with, and is constituted in accordance with, the requirements of the TriCouncil Policy Statement: Ethical Conduct for Research Involving Humans (TCPS 2); the International Conference on Harmonisation Good Clinical Practice Consolidated Guideline (ICH GCP); Part C, Division 5 of the Food and Drug Regulations; Part 4 of the Natural Health Products Regulations; Part 3 of the Medical Devices Regulations and the provisions of the Ontario Personal Health Information Protection Act (PHIPA 2004) and its applicable regulations. The HSREB is registered with the U.S. Department of Health & Human Services under the IRB registration number IRB 00000940.

Please do not hesitate to contact us if you have any questions.

Sincerely,

Nicola Geoghegan-Morphet, Ethics Officer on behalf of Dr. Joseph Gilbert, HSREB Chair

***Note: This correspondence includes an electronic signature (validation and approval via an online system that is compliant with all regulations).***

## Appendix C Magnetic resonance imaging sequences

| Sequence | Bilateral | Plane | Fat suppression | Field of view (mm) | TR, TE (ms) | Echo trains per slice | Slice thickness (mm) |
|---|---|---|---|---|---|---|---|
| **T1-weighted turbo spin echo Achilles tendon** | Yes | Sagittal | None | 200 | 665, 12 | 102 | 3 |
| **T2-weighted turbo spin echo Achilles tendon** | Yes | Sagittal | Yes | 200 | 4000, 79 | 22 | 3 |
| **T2-weighted turbo spin echo Achilles tendon** | Yes | Sagittal | No | 200 | 3500, 77 | 29 | 3 |
| **T2-weighted turbo spin echo Achilles tendon** | Yes | Axial | Yes | 300 | 9820, 78 | 17 | 3 |
| **T1-weighted turbo spin echo** | Yes | Axial | No | 350 | 848, 13 | 114 | 3 |
| **T1-weighted turbo inversion recovery** | Yes | Axial | Yes | 350 | 5120 | 40 | 3 |
| **T2-weighed SPACE (isotropic)** | Involved only | 3-dimensional | No | 230 | 2500, 223 | n/a | 0.9 |

**Appendix D Achilles Tendon Total Rupture Score**

Initials: _____

# ATRS

## *(Achilles Tendon Total Rupture Score)*

PID: _____ Empower: _____

All questions refer to your limitations/difficulties related to your injured Achilles tendon.
Answer every question by grading your limitations/symptoms from 0-10.
*Remember* (0= Major limitations and 10= No limitations).

**Please circle the number that 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 (No limitations)*

2. Are you limited due to fatigue in the calf/Achilles tendon/foot?
*0 1 2 3 4 5 6 7 8 9 10 (No limitations)*

3. Are you limited due to stiffness in the calf/Achilles tendon/foot?
*0 1 2 3 4 5 6 7 8 9 10 (No limitations)*

4. Are you limited due to pain in the calf/Achilles tendon/foot?
*0 1 2 3 4 5 6 7 8 9 10 (No limitations)*

5. Are you limited during activities of daily living?
*0 1 2 3 4 5 6 7 8 9 10 (No limitations)*

6. Are you limited when walking on uneven surfaces?
*0 1 2 3 4 5 6 7 8 9 10 (No limitations)*

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 (No limitations)*

8. Are you limited during activities that include running?
*0 1 2 3 4 5 6 7 8 9 10 (No limitations)*

9. Are you limited during activities that include jumping?
*0 1 2 3 4 5 6 7 8 9 10 (No limitations)*

10. Are you limited in performing hard physical labour?
*0 1 2 3 4 5 6 7 8 9 10 (No limitations)*

**Thank you very much for completing all the questions in this questionnaire.**

**Appendix E Leppilahti Score**

PID: _____ Empower: _____ Initials: _____

## LEPPILAHTI SCORE

| | |
|---|---|
| **Pain** | |
| None | 15 |
| Mild, no limitations on recreational, but not daily activities | 10 |
| Moderate, limitation on recreational, but not daily activities | 5 |
| Severe, limitations on recreational and daily activities | 0 |
| **Stiffness** | |
| None | 15 |
| Mild, no limitations on recreational, but not daily activities | 10 |
| Moderate, limitation on recreational, but not daily activities | 5 |
| Severe, limitations on recreational and daily activities | 0 |
| **Calf muscle weakness (subjective)** | |
| None | 15 |
| Mild, no limitations on recreational, but not daily activities | 10 |
| Moderate, limitation on recreational, but not daily activities | 5 |
| Severe, limitations on recreational and daily activities | 0 |
| **Footwear restrictions** | |
| None | 10 |
| Mild, most shoes tolerated | 5 |
| Moderate, unable to tolerate fashionable shoes, modified shoes tolerated | 0 |
| **Active range of motion (ROM) difference between ankles** | |
| Normal (<6°) | 15 |
| Mild (6°-10°) | 10 |
| Moderate (11°-15°) | 5 |
| Severe (>15°) | 0 |
| **Subjective result** | |
| Very satisfied | 15 |
| Satisfied with minor reservations | 10 |
| Satisfied with major reservations | 5 |
| Dissatisfied | 0 |
| **Isokinetic muscle strength (score)** | |
| Excellent | 15 |
| Good | 10 |
| Fair | 5 |
| Poor | 0 |

**Appendix F Study letter of information and consent form**

Western HealthSciences

Study Title: Operative vs non-operative treatment of acute Achilles tendon rupture: A >10 year follow up

Principal Investigator: Dr. Kevin Willits MD, Schulich School of Medicine and Dentistry, Western University [redacted]
Research Team: Michaela Khan BA, School of Kinesiology [redacted]
Trevor Birmingham PhD, School of Physical Therapy [redacted]
Dianne Bryant PhD, School of Physical Therapy [redacted]

**Letter of Information**

Dear Potential Participant,

The purpose of this letter is to provide you with the information you require to make an informed decision about participating in this study, entitled "Operative vs non-operative treatment of acute Achilles tendon rupture: A >10 year follow up". The study will take place within the Wolf Orthopaedic Biomechanics Laboratory/ Fowler Kennedy Sport Medicine Clinic (WOBL/ FKSMC; inside Western University's 3M Building) and the Centre for Functional and Metabolic Mapping (CFMM), located on the Western University campus. The study is being conducted by Michaela Khan, MSc. student in the School of Kinesiology at Western University, Dr. Trevor Birmingham, Professor in the School of Physical Therapy, Dr. Dianne Bryant, Associate Professor in the School of Physical Therapy and Dr. Kevin Willits, Associate Professor at the Schulich School of Medicine and Dentistry. The overall purpose of this study is to compare long-term (>10 years) outcomes in patients who had an acute Achilles tendon rupture (AATR) and were randomized to surgical repair with accelerated functional rehabilitation versus accelerated functional rehabilitation alone. This research is funded by the Transdisciplinary Bone & Joint Training Award, Bone & Joint Institute, Western University.

Conflict of Interest
We wish to make you aware that Dr Dianne Bryant, who is one of this study's investigators, is the Owner and Director of EmPower Health Research Inc. However, she is not paid a salary nor will receive any personal benefits or compensation from this study. EmPower data services are being provided as an in-kind contribution.

Study Criteria:
You are invited to participate in this study because you were part of a prior study (Willits et al., 2010) investigating outcomes of patients with AATRs. Current inclusion criteria includes all patients randomized from Willits et al. (2010) who are 10+ years post-injury. We will be recruiting 82 local participants.

Procedures:
You are being asked to attend a single session that will include questionnaires, a magnetic resonance image (MRI) scan and functional tests. The visit will be up to 2 hours in length.

You will first be asked to fill out the Leppilahti Score and Achilles Tendon Total Rupture Score regarding any symptoms you may be experiencing. Then, MRI scans of your lower legs will be performed at the CFMM (approx. 1 hour). You will lie supine on the MRI table then enter the MR tunnel feet first. Following the scan, we will return to WOBL where we will complete the remainder of the study. We will start by measuring your ankle passive range of motion and calf circumference. Next, your ankle muscle strength will be evaluated using the BIODEX system. During this test and for the remainder of the study, you will wear sensors over various positions on your lower legs to measure muscle activity. You will be positioned in a reclined chair with your ankle strapped onto an immovable cushion. You will be asked to plantarflex (point toes down) and dorsiflex (pull toes up) your ankle as hard as you can. Following strength testing, the remainder of the study will take place on a treadmill. We will place retro-reflective markers over various bone and muscle landmarks on your legs and motion sensing cameras around the treadmill will record the position of these markers. First, we will evaluate how your ankle moves during walking trials on level ground, inclines and declines. Next, you will perform maximal one-legged jumps. You will start from an upright position, make a downward movement by flexing your knees and hips, then immediately extend your knees/ hips to jump vertically off the ground as high as you can. Finally, we will assess your one-legged maximum heel-rise height and the total number of heel-rises you can perform. You will perform heel-rises to a metronome set at 60 beats per minute on a box with an incline of 10°.

Possible Risks and Harms:

There are minimal known risks for participating in this study. If you are harmed as a direct result of taking part in this study, all necessary medical treatment will be made available to you at no cost.

The electronic data will be held in EmPower and is protected by a username and password. As we are collecting identifiable and personal health information, there is always a risk of a privacy breach. If we become aware that this has happened, we would inform you immediately.

There are no known biological risks associated with MR imaging. Some people cannot have an MRI because they have some type of metal in their body. For instance, if you have a heart pacemaker, artificial heart valves, metal implants such as metal ear implants, bullet pieces, chemotherapy or insulin pumps or any other metal such as metal clips or rings, you cannot have an MRI. During this test, you will lie in a small closed area inside a large magnetic tube. Some people may get scared or anxious in small places (claustrophobic). An MRI may also cause possible anxiety for people due to the loud noises made by the machine. You will be given ear plugs to reduce the noise to a comfortable level.

The MRI experiments carried out for this study are collected solely for scientific purposes. The data that is collected is not optimized to make clinical diagnoses, and the research team involved in these experiments are not trained to make medical evaluations. When participating, you agree that the experimenters are not expected to arrive at a clinical interpretation of the data collected.

Nevertheless, there is a small possibility that a potential abnormality might be observed –

otherwise known as an incidental finding. If this occurs you will be notified of the issue by the principal investigator of the study who will assist you with your options for following up. Investigators are not responsible for the outcome of medical follow-up or for any incurred costs during medical follow-up. When participating, you agree to the possibility of being informed about potential medical problems, according to the above-described procedure. If you do not agree to the potential risk of an incidental finding, you cannot participate in this study

It is possible that you could fall, injure or re-injure yourself while performing functional tests. However, the risks are no greater than those encountered with typical everyday life. All bilateral tests will begin with your non-affected before affected leg. During the walking tests, it is possible for you to lose your balance and sustain an injury (sprain or bruise). The treadmill has handrails on either side that you can grab and you will wear a safety harness. There are also safety mechanisms that automatically shut down the treadmill if you fall. You can instruct the operator to stop the test at any time.

The sensors and retro-reflective markers only sense motion and muscle activity – they do not send electricity to you and are not painful. Motion capture cameras will only record marker position and will not capture your identity.

Benefits:
You will not receive any direct benefits from participating in this study. The results of this study may provide further information to clinicians and researchers and help in identifying new appropriate treatments for clinical populations in the future.

Compensation:
You will not receive any compensation for participating. A parking token will be provided if you need one.

Participation:
Participation in the study is voluntary. You may refuse to participate, withdraw consent or/ and withdraw your data from the study at any time with no effect on you. Should you choose to withdraw from this study, we will keep all data obtained up to the point that you choose to withdraw. You may decline being contacted for further research that may continue from this project. Participation in this study does not prevent you from participating in other research studies at the present time or in the future. You do not waive any legal rights by signing the consent form.

Confidentiality:
Your individual results will be held in strict confidence. No person other than the investigators will be given access to your records without your expressed permission. When the results are reported, individual records will be coded or reported as group data. Computer files of data collected will be stored on an encrypted hard drive in the WOBL located behind secure-locking doors. Written records will be secured in a locked cabinet in the WOBL. The information collected will be retained for a period of 15 years, as per guidelines for research records. Representatives of Western University Health Sciences Research Ethics Board may require access to your study-related documents to oversee the ethical conduct of this study. Representatives of Lawson Quality Assurance Education

Program may require access to your study-related documents to ensure that proper laws and guidelines are being followed.

In any publication, presentation or report, your name will not be used and any information that discloses your identity will not be released or published unless required by law.

The data that is collected from you is managed by a company called EmPower Health Research. Any information provided by you is protected by a username and password. It travels in a scrambled format to a server (storage computer) that is located in Montreal, Canada. Your email address is part of this database. Instructions for logging into the database will be provided by the research assistant. The company that houses the server is a professional company with extremely high standards of physical and virtual security. We want to let you know however, that even with this high level of security, there is always a remote chance that your information could be accessed or "hacked" by someone who is not supposed to have your information. If we became aware that this has happened, we would inform you immediately.

Contact Information:

If you agree to participate in this study, please complete the attached consent form. If you have any other questions, please feel free to contact Michaela Khan by email at [redacted] If you have any questions related to the ethics of the research and would like to speak to someone outside of the research team, please contact The Office of Human Research Ethics at [redacted] or [redacted] or by email at [redacted]

Sincerely,

Michaela Khan, BA
Master of Science graduate student, School of Kinesiology,
Western University, London, Ontario

Dr. Kevin Willits, MD
Associate Professor, Schulich School of Medicine and Dentistry,
Western University, London, Ontario

Dr. Trevor Birmingham, PhD
Professor, School of Physical Therapy,
Western University, London, Ontario

Dr. Dianne Bryant, PhD
Associate Professor, School of Physical Therapy,
Western University, London, Ontario

This letter is yours to keep for future reference.

Western HealthSciences

**Consent Form**

Title: Operative vs non-operative treatment of acute Achilles tendon rupture: A >10 year follow up

Principal Investigator: Dr. Kevin Willits, MD.

Research Team: Michaela Khan, BA.
Trevor Birmingham, PhD.
Dianne Bryant, PhD.

I, _____ have read the Letter of Information, have had the nature of the study explained to me and I agree to participate. All questions have been answered to my satisfaction.

_____ _____

Participant Name (please print) Print Date

_____ _____

Signature of Participant Print Date

_____ _____

Researcher Name (please print) Print Date

_____ _____

Signature of Researcher Print Date

# Curriculum Vitae

**Name:** Michaela Christina MacKenzie Khan

**Post-secondary Education and Degrees:**
Western University
London, Ontario, Canada
2013-2017 B.A. Honors Specialization in Kinesiology

**Honours/Awards:**

Faculty of Health Sciences Graduate Conference Travel Award (Fall) ($210)
Western University, 2019

Top Podium Presentation (Master's)
Health & Rehabilitation Sciences Graduate Research Conference
Western University, 2019

2nd Place Podium Presentation
4th Annual Kinesiology Graduate Student Association Research Symposium
Western University, 2019

Summer School on Wearable Sensors for Balance and Movement Bursary ($1,200)
Canadian MSK Rehab Research Network, 2019

Kinesiology Graduate Student Conference Travel Award ($418)
Western University, 2019

Faculty of Health Sciences Graduate Conference Travel Award (Summer) ($181)
Western University, 2019

Sun Life Financial Scholarship ($1,000)
U SPORTS, 2018

Top Poster Presentation
4th Annual Kinesiology Graduate Student Association Research Symposium
Western University, 2018

Western Graduate Research Scholarship ($12,000)
Western University, 2017-2019

Transdisciplinary Bone & Joint Training Award ($10,000)
Bone & Joint Institute, Western University, 2017-2019

Ontario Graduate Scholarship ($30,000)
Western University, 2017-2019

Canada Graduate Scholarship – Master's (NSERC)
University of Waterloo (declined), 2017

President's Graduate Scholarship ($10,000)
University of Waterloo (declined), 2017

Bronze W Award
Western University, 2016

The Parents Fund Award in the Faculty of Health Sciences ($500)
Western University, 2016

UWO In-Course Scholarship ($700)
Western University, 2015

International Learning Award ($1,000)
Western University, 2015

Jana Lyn Elise Oldham Award ($700)
Western University, 2015

OUA Academic Achievement Award
Ontario University Athletics, 2014-2019

First Colour Award
Western University, 2014-2016

Dean's Honor List
Western University, 2014-2017

**Related Work Experience:**

Research Assistant
SoleScience: Pedorthics and Custom Orthotics
London, Ontario, 2018-2019

Teaching Assistant
Anatomy and Cell Biology 2221: Functional Human Anatomy
Western University, 2018

Senior Staff, Clinical Skills Learning Program, Schulich School of Medicine and Denstistry
Western University, 2017-2019

Research Assistant, Motor Control Laboratory
University of Windsor, 2017 & 2019

Assistant Squash Coach, Women's Varsity Squash Team
Western University, 2016-2018

Research Volunteer, Neurovascular Research Laboratory
Western University, 2015-2016

**Publications:**

Heath, M., Manzone, J., Khan, M., & Jazi, S. D. (2017). Vision for action and perception elicit dissociable adherence to Weber's law across a range of 'graspable' target objects. *Experimental brain research*, *235*(10), 3003-3012.

Schulz, J. M., Birmingham, T. B., Atkinson, H. F., Woehrle, E., Primeau, C. A., Lukacs, M. J., Al-Khazraji, B. K., Khan, M. C., Zomar, B. O., Petrella, R. J., & Beier, F. (2019). Are we missing the target? Are we aiming too low? What are the aerobic exercise prescriptions and their effects on markers of cardiovascular health and systemic inflammation in patients with knee osteoarthritis? A systematic review and meta-analysis. *British Journal of Sports Medicine*.

Balsdon, M., Khan, M., Dombroski, C. Arch Height Index Values in a Symptomatic Population. *Journal of the American Podiatric Medical Association*. Submitted for publication August 2019.