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From *in silico* to insight:
Using computational models to guide the management of Achilles tendon ruptures

Pedro Miguel Gonçalves Diniz

Supervisor: Doctor Gino Matheus Melanie Johannes Kerkhoffs
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Thesis approved in public session to obtain the PhD Degree in
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Jury final classification: **Pass with Distinction and Honour**

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2023

To Sara

ABSTRACT

This Ph.D. thesis details research on Achilles tendon ruptures (ATRs) using multiple methods, including finite element analysis, systematic literature review, meta-analysis, clinical assessment, cost-effectiveness analysis, and machine learning.

A finite element model of the Achilles tendon is developed, incorporating aponeurotic and free tendon regions. This model first studies the injury risk associated with free tendon length. It suggests that variations in the cross-sectional area of subtendons, rather than free tendon length, may increase rupture risk. The model is also used to evaluate the progression risk of partial tendon ruptures with less than 50% loss of continuity. Ruptures affecting less than 50% of the tendon may progress under loads related to an early rehabilitation protocol.

Next, a systematic literature review evaluates the impact of tendon elongation on clinical, strength, and biomechanical outcomes. There is fair evidence that elongation post-ATRs negatively affects biomechanical parameters. A network meta-analysis of cadaveric studies shows that a modified triple-Kessler stitch is the technique most likely to minimize tendon elongation.

The results of a case series of patients with acute ATRs treated with an endoscopic flexor hallucis longus (FHL) transfer are presented. The technique demonstrates promising results. A cost-effectiveness analysis shows a favorable profile compared to conservative treatment, open surgery, and minimally invasive surgery.

Finally, post-ATR performance in elite soccer players is evaluated using data mining tools and machine learning. The analysis shows that most players improve their average match time in the first year post-injury. A machine learning classifier predicts players' return to similar or improved levels, with pre-injury performance being crucial. Despite decreased match participation, soccer players maintain performance levels when compared to matched controls considering a weighted plus/minus metric.

Keywords Achilles tendon ruptures, finite element analysis, cost-effectiveness analysis, data analytics, meta-analysis.

RESUMO

Esta tese de Doutoramento apresenta estudos sobre rupturas do tendão de Aquiles (RTAs) utilizando múltiplas abordagens: análise de elementos finitos, revisão sistemática da literatura, meta-análise, avaliação clínica, análise de custo-eficiência e aprendizagem automática (AA).

Um modelo de elementos finitos do tendão de Aquiles, incorporando as regiões aponevrótica e livre, é desenvolvido. Primeiramente, estuda-se a influência do comprimento do tendão livre no risco de lesão. Verifica-se que variações na área de secção transversal dos subtendões, mas não no comprimento do tendão livre, podem aumentar o risco de ruptura. Seguidamente, avalia-se o risco de progressão de rupturas parciais com menos de 50% de perda de continuidade, constatando-se que estas podem progredir com cargas associadas à reabilitação funcional precoce.

Seguidamente, o impacto do alongamento pós-RTA nos resultados clínicos, medições de força e parâmetros biomecânicos, é avaliado mediante revisão sistemática da literatura. Encontra-se evidência razoável de um efeito deletério em parâmetros biomecânicos. Segundo uma meta-análise em rede de estudos em cadáver, o triplo-Kessler modificado é a técnica cirúrgica provavelmente mais eficaz na minimização do alongamento pós-RTA.

Resultados clínicos promissores da transferência endoscópica do longo flexor do hallux em doentes com RTAs agudas são apresentados. Uma análise preliminar de custo-eficiência mostra um perfil favorável em comparação com o tratamento conservador, cirurgia aberta e cirurgia minimamente invasiva.

Finalmente, mineração de dados e AA são usadas para avaliar o desempenho pós-RTA em futebolistas de elite. A maioria dos jogadores aumenta os minutos médios jogados no primeiro ano pós-lesão. O desempenho pré-lesão é crucial para a previsão do retorno dos jogadores a níveis semelhantes ou superiores de participação em jogos usando um classificador de AA. Comparando com controlos, estes jogadores mantiveram o desempenho, conforme uma métrica ponderada mais/menos, apesar da redução nos minutos jogados.

Palavras-chave Rupturas do tendão de Aquiles, análise de elementos finitos, análise de custo-efectividade, análise de dados, meta-análise.

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ABBREVIATIONS

AATR	Acute Achilles Tendon Rupture
AOFAS	American Orthopaedic Foot and Ankle Society
APD	Anteroposterior Diameter
AT	Achilles Tendon
ATR	Achilles Tendon Rupture
ATRA	Achilles Tendon Resting Angle
ATRS	Achilles Tendon Total Rupture Score
AUROC	Area Under the Receiver Operating Characteristic Curve
CEA	Cost-Effectiveness Analysis
CI	Confidence Interval
CPT	Current Procedural Terminology
CSA	Cross-sectional Area
CTRL	Matched-Control Group
DVT	Deep Venous Thrombosis
EFR	Early Functional Rehabilitation
ESWT	Extracorporeal Shock Wave Therapy
FAOS	Foot and Ankle Outcome Score
FE	Finite Element
FEA	Finite Element Analysis
FFD	Free-Form Deformation
FHL	Flexor Hallucis Longus

FHL | Flexor Hallucis Longus

FOV | Field Of View

HRH | Heel-Rise Height

HRQoL | Health-Related Quality of Life

HRW | Heel-Rise Work

ICER | Incremental Cost-Effectiveness Ratio

iEMG | Integrated EMG

IQR | Interquartile Range

MCC | Maximum Calf Circumference

MFSS | Multifilament Stainless Steel

MIS | Minimally Invasive Surgery

ML | Machine Learning

MLD | Mediolateral Diameter

MPM | Minutes Played per Match

MRI | Magnetic Resonance Imaging

MTJ | Myotendinous Junction

MV | Muscle Volume

MVIC | Maximum Voluntary Isometric Contraction

N | Newtons

NMA | Network Meta-Analysis

NMB | Net Monetary Benefit

ORS | Open Revision Surgery

PARS | Percutaneous Achilles Repair System

PAS | Physical Activity Scale

PM | Plus/Minus

PRISMA | Preferred Reporting Items for Systematic Reviews and Meta-Analyses

PROMs | Patient Reported Outcome Measures

PRP | Platelet-Rich Plasma

PSA | Probabilistic Sensitivity analysis

QALYs | Quality-Adjusted Life-Years

QUIPs | Quality in Prognosis Studies

RMSD | Root Mean Square Deviation

ROM | Range of Motion

RTP | Return To Play

RTW | Return-To-Work

SCs | Statistical Correlations

SD | Standard Deviation

SPSS | Statistical Package for the Social Sciences

SUCRA | Surface Under the Cumulative Ranking Curve

TAS | Tegner Activity Scale

US | Ultrasound

VAS | Visual Analog Scale

WHPs | Wound Healing Problems

WTP | Willingness-To-Pay

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Section Alpha

Contextualization

CHAPTER 1
General introduction

INTRODUCTION

In Greek mythology, Achilles was a Greek hero of the Trojan War. He was said to be the most capable Greek army soldier, practically invincible, with his sole weakness being his heel. He was said to be this way because his mother, Thetis, held him by one of his ankles while dipping him in River Styx, leaving this region untouched by the waters that would grant him immortality. Accordingly, in Greek mythology, Achilles died because of a poisonous arrow to his ankle. To this legend, the Achilles tendon (AT), known as the calcaneal tendon in the modern *terminologia anatomica*, owes its name. First introduced in 1705, this eponym's enduring nature, despite being renegaded by the Anatomical Society in 1998, is a testament to its relevance [14, 41].

In a way, Achilles tendon ruptures (ATRs) draw some parallelism between injuries in elite athletes and the history of the warrior Achilles. In *The Iliad*, which is a major ancient Greek epic poem credited to Homer [25], Achilles' mother predicted that her son would live a long life should he decide to relinquish his glory and return home or would die young, but forever famous if he decided to stay in Troy and fight:

> "My mother, Thetis of the silvery feet,
> Tells me of two possible destinies
> carrying me toward death: two ways:
> if on the one hand I remain to fight
> around Troy town, I lose all hope of home
> but gain unfading glory; on the other,
> if I sail back to my own land my glory
> fails – but a long life lies ahead for me."

in Homer's *The Iliad*,
as translated by Robert Fitzgerald

Most ATRs occur during sporting activities [32, 34], with several hypothetical contributing factors. For example, the AT is subject to loads nearing 8 to 12 times bodyweight during running [10, 20] and even more during jumping, and those involved in competitive sports may accumulate several hours of such activities per week. Such increased demand on the AT may lead to progressive tendon damage, dysrepair, and degeneration, eventually leading to rupture [4]. In addition, the AT exhibits limited tissue renewal potential and thus little regenerative capacity [23]. In a study using the ^{14}C bomb-pulse method, which is based on the stark rise in ^{14}C levels resulting from nuclear bomb tests between 1955 and 1963, it was revealed that AT core concentrations of ^{14}C in 28 forensic samples were similar to atmospheric levels in the first 17 years of the donors' lives, signifying limited tissue renewal after height growth. In contrast, ^{14}C levels in samples of muscle tissue indicated continuous turnover.

Even if at different scales, all athletes, professional or otherwise, engaged in competitive sports are striving for glory. Perhaps it was already observed in ancient Greece that, despite their otherwise mighty bodies, great fighters and athletes tended to suffer injuries in their heels, and such observation served as inspiration for the myth of the warrior Achilles.

MOTIVATION AND RESEARCH GOALS

Achilles tendon ruptures are common injuries. Notably, the incidence of ATRs is reported to have increased in recent decades [15, 33, 53], with an incidence of 32.3 per 100.000 person-years recently reported in Finland [34]. The incidence of ATRs has been rising since the 1950s [33], which has been, at least partially, linked to a growing interest in sporting activities as populations moved from rural areas to cities and living conditions improved [42]. These injuries are 3 to 10 times more common in men than women and often occur in recreational athletes aged between 30 and 40 [15]. The largest rise in incidence, however, has been observed in older patients [24, 35].

The triceps surae muscle comprises the soleus and gastrocnemius muscles, with the AT resulting from these muscles' subtendons confluence [44]. The soleus and gastrocnemius subtendons begin as independent muscle aponeuroses [38] and merge approximately at 38 to 43% of the distance from the calcaneal insertion to the fibular head [13]. Accordingly, the AT can be divided into two regions: aponeurotic and free tendon regions. The aponeurotic region begins at the distal gastrocnemius myotendinous junction (MTJ) and ends at the distal soleus MTJ. Conversely, the free tendon region begins in the distal soleus MTJ and ends in the calcaneal insertion. The distinguishing feature between these two segments is that the free tendon region does not have muscle fibers attaching directly to it [26]. One notable characteristic of the AT is the twisting of the subtendons, which twist around each other – counter-clockwise in a right limb –[12] before inserting into the calcaneus [7]. Patterns of twisting are typically grouped into small, moderate, or large twisting [7, 12], with values ranging from 30 to 150 degrees having been reported [50]. The AT subtendons can also slide independently [21], with the amount of sliding decreasing with aging [56].

Ruptures of the AT are usually located between 2 and 7 cm from the calcaneal insertion, but may extend more proximally [49]. This rupture location has been classically attributed to "poor regional vascularity", but this concept has since been challenged [8]. Regardless, degenerative changes are typically, but not always [48], present before rupture [29]. Of note, up to 4% of patients with AT tendinopathy will sustain an ATR [62] Accordingly, it is commonly accepted that "normal tendons do not rupture", and ATRs may be placed at the end of the tendinopathy spectrum [4, 5], more so considering that the events leading to an ATR are a common occurrence during sports practice [9, 35], and almost always of inconspicuous nature. Furthermore, the treatment of partial ATRs, which may be the result of an acute event or a consequence of chronic tendinopathy [16], lacks well-established guidelines. Conservative treatment is often recommended for partial ATRs affecting less than 50% of the tendon's width, but experimental evidence supporting this "50% rule" is currently missing from literature.

Thus, one of the research goals of the present thesis was to develop and validate a finite element model of the AT, including the aponeurotic and free tendon regions, and use said model to investigate risk factors for AT tendinopathy and progression of partial ruptures, commonly found in degenerative ATs [16], to complete ATRs.

The optimal treatment of ATRs is controversial. Currently accepted options include conservative treatment and surgical repair [11, 28, 55], with early functional rehabilitation (EFR) being advisable in both approaches, as EFR has been found to increase patient satisfaction [63], promote earlier return-to-work [39, 40] and enhance tissue healing [51, 52, 59], compared to immobilization. In addition, several repair techniques can be found in the literature [6, 31]. However, persistent functional impairments are common regardless of treatment choices [45]. Specifically, most patients with ATRs will not fully recover regarding symptoms [45], level of physical activity [45], and strength [2]. The outcomes of ATRs may be worsened by complications. Namely, re-ruptures and major wound healing problems can have lasting and devastating effects [46, 60]. For instance, patients with re-ruptures, which can occur in 15% of cases [3], will have worse long-term clinical and functional outcomes than successfully treated patients with primary ruptures [60]. Similarly, patients with major wound healing complications and infections, which affects mainly patients subjected to open repairs [18], will also experience a marked decrease in functional outcomes, namely isokinetic strength [46].

Therefore, a second research goal of this thesis was to contribute to the improvement of treatment outcomes of ATRs by evaluating whether avoiding post-rupture AT elongation can be a worthy objective and, if so, by seeking means to do so while avoiding other complications.

Endoscopic flexor hallucis longus (FHL) transfer has recently emerged as a proposed treatment for chronic and complex ATRs [1, 36, 37], but its outcomes in acute injuries have yet to be investigated. Of note, FHL hypertrophy is frequently observed after ATRs [22]. Previous research has shown a correlation between soleus muscle atrophy and hypertrophy of the FHL and other deep flexors [22]. Therefore, re-routing the FHL in acute injuries to a location near the AT insertion could offset plantarflexion strength deficits and inferior mechanical properties of the ruptured AT. In addition, an FHL transfer may have the advantage of preemptively treating AT re-ruptures, as this is an acceptable method of treating this complication [17]. Furthermore, given the enduring debate between operative and conservative treatment proponents [43], which extends to cost-effectiveness analyses [30, 58, 61], a fresh perspective is of interest.

Thus, another research goal of this thesis was to assess the clinical outcomes of an endoscopic FHL transfer in treating acute ATRs and compare this approach to current treatments in a health economic analysis.

Finally, ATRs can be career-threatening injuries for elite athletes. A substantial percentage of players prematurely ending their careers after suffering such injuries has been noted in several sports, including American football [47], basketball [35], and soccer [54]. Furthermore, decreased sports performance has also been previously observed in players after return-to-play [19, 27, 35, 47, 54, 57]. In the sport of soccer, however, such impact has been evaluated strictly in the realm of returning to the same league [19], career length [54], and simple performance metrics [54, 57], such as goals scored or fouls committed, and mainly in cross-sectional analyses.

Hence, the last goal of this thesis was to improve our understanding, from a sports performance perspective, of how recovery from an ATR unfolds over time in soccer players and assess possible predicting factors.

RESEARCH QUESTIONS

Considering the research goals mentioned above, the following research questions, which this thesis intends to enlighten, were formulated:

1. Can a finite element model of the Achilles tendon, that includes both the aponeurotic and free tendon regions and features subtendon sliding, be developed and validated? Specifically, the two sub-research questions will also be considered:

- **a.** Do longer tendons have a higher risk of rupture or exhibit increased strains during simulated loading?
- **b.** Should the current cut-off of 50% for surgical treatment of partial ATRs be reconsidered?

2. Is post-rupture AT elongation a relevant problem? If so, so the following sub-research question will be addressed:

> **a.** What surgical technique will provide the least risk of tendon elongation?

3. Is an endoscopic FHL transfer a viable approach for acute ruptures?

> **a.** If so, does this technique have a favorable cost-effectiveness profile compared to current treatments?

4. How does match participation evolve following ATRs in elite soccer players? In particular:

> **a.** What features would be more important for predicting match participation following rupture?
>
> **b.** How does match performance in players suffering ATRs compare with matched controls before and after injury?

STRUCTURE OF THE THESIS

This thesis is organized into six sections. A schematic representation of how this thesis is structured, in relation to research goals and questions, can be found in Figure 1.

INJURY-RECOVERY STAGE	SECTION	RESEARCH QUESTION
	Alpha	**CONTEXTUALIZATION** General introduction State-of-the-art review of Achilles tendon disorders
Before injury	**Beta**	**USING FINITE ELEMENT MODELING TO STUDY RISK FACTORS FOR ACHILLES TENDON RUPTURES** 1. Can a finite element model of the Achilles tendon, that includes both the aponeurotic and free tendon regions and features subtendon sliding, be developed and validated? 2. Do longer tendons have a higher risk of rupture or exhibit increased strains during simulated loading? 3. Should the current cut-off of 50% for surgical treatment of partial ATRs be reconsidered?
After injury	**Gamma**	**CONTRIBUTING TO THE IMPROVEMENT OF TREATMENT OUTCOMES IN ACHILLES TENDON RUPTURES** 1. Is post-rupture AT elongation a relevant problem? 2. What surgical technique will provide the least risk of tendon elongation?
After injury	**Delta**	**A NOVEL TREATMENT APPROACH TO ACHILLES TENDON RUPTURES** 1. Is an endoscopic FHL transfer a viable approach for acute ruptures? 2. Does this technique have a favorable cost-effectiveness profile compared to current treatments?
After treatment	**Epsilon**	**USING ADVANCED DATA ANALYTICS AND MACHINE LEARNING MODELS FOR PROGNOSTICS IN ELITE ATHLETES** 1. How does match participation evolve following ATRs in elite soccer players? 2. What features would be more important for predicting match participation following rupture? 3. How does match performance compare with matched controls before and after injury?
	Zeta	**GENERAL DISCUSSION** General overview of study results Future research

FIGURE 1 | Schematic representation of this thesis' structure, regarding research goals and questions.

The first section, Alpha, in which this chapter is included, relates to the contextualization of ATRs in AT disorders. It starts with this chapter and is followed by a state-of-the-art review of Achilles tendon disorders and their treatment in athletes.

The following section, Beta, describes the development and validation of a finite element model of the AT and the use of the said model to address two related research questions. Specifically, as mentioned above, the model was used to (a) evaluate if differences in free tendon length would influence the results of a simulated rupture experiment and (b) whether partial ruptures could progress to complete ruptures under loads comparable to those applied on an early functional rehabilitation protocol for ruptures with less than 50% of the tendon width.

Section Gamma pertains to research on whether post-rupture AT elongation is a significant problem and how it can be minimized. This section starts with a systematic review of clinical studies, examining available data to assess if tendon elongation may negatively influence clinical strength and biomechanical outcomes. Next, a statistical model is used to compare the results of biomechanical studies of repair techniques in cadaveric models and rank these techniques regarding their resistance to construct elongation and load-to-failure.

Section Delta aims to evaluate endoscopic flexor hallucis longus transfers as a treatment approach to ATRs. This section includes two studies. First, a prospective case series of patients with ATRs treated with an isolated endoscopic FHL transfer is presented bringing clinical insights on the results of this treatment approach for acute ATRs. Second, an early cost-effectiveness analysis is conducted to compare this option with current treatments for ATRs.

Section Epsilon presents the results of two studies performed using advanced data mining and analytics using publicly available data. The first study aimed to evaluate the match participation after ATRs in elite soccer players and use of a machine learning classifier to assess which features were more important for predicting return-to-performance in this population. The second study used a plus/minus weighted metric to quantify the performance of players with ATRs and matched controls before and after injury while assessing factors correlating with the performance one year after injury.

Finally, Section Zeta provides an overview of the results of the studies conducted as part of this thesis, and possible directions for future research.

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CHAPTER 2

Current Concepts Review: Achilles Tendon Related Disorders in Athletes

Adapted from:
Piedade SR, Diniz P, Pereira H, Mouraria GS, Queiroz RD, Ferreira DM (2022) CrossFit, Spinning, Aerobics. In Piedade SR, Neyret P, Espregueira-Mendes J, Cohen M, Hutchinson MR (eds). Specific Sports-Related Injuries, Springer, Berlin, Germany, pp. 221-238

INTRODUCTION

FIGURE 2 | Superficial anatomy.

Injuries related to the Achilles tendon are common problems and some of the most researched topics regarding the foot and ankle. These can involve the tendon, paratenon or surrounding bursas. Injuries affecting the tendon can be divided into insertional and non-insertional. As an attempt to make more uniform the description of the pathology around this tendon, a classification combining clinical, image and histology focused on practical approach has been proposed [23].

As any other tendon it has a biomechanical behaviour and physical strain during adequate training might have a positive effect but a threshold exists, different in every individual or athlete above which strain will, in contrary, have a negative, deleterious effect on the tendon, leading to pathologic degenerative changes [2]. This is the strongest tendon of the body [40].

ANATOMY

The Achilles tendon is located in the superficial posterior compartment of the leg (Figure 2) and is formed by the conjoining of the tendons of the gastrocnemius and soleus muscles, with the plantaris tendon being also included on occasion [17]. Total length is approximately 15 cm and full incorporation of the soleus and gastrocnemius tendons is evident at 8-10 cm from the calcaneal insertion [9, 18]. The Achilles tendon undergoes a clockwise rotation in a left limb, and counter clockwise rotation in a right limb, from proximal to distal, as it descends towards the calcaneus. The greatest degree of torsion is observed in the most anterior part of the tendon [49]. One very important aspect related to pathology is the vascularity pattern, which includes two hypovascular zones, one close to its insertion and a second around 5-7 cm more proximal (Figure 3) [15]. This is particularly relevant in high-level sports, individual or team-sports due to the frequency of loads and eccentric work.

FIGURE 3 | Dissection of Achilles tendon.

DIAGNOSIS AND TREATMENT

Mid-Portion Achilles Tendinopathy

Achilles tendinopathy is one of the most commonly studied disorders of the foot and ankle [58]. The incidence rate of mid-portion Achilles tendinopathy (Table 1) in the Dutch population is 2.35 per 1000 registered patients with ages between 21 and 60 years, with 35% of the cases being related with sports activity [36].

TABLE 1 | Mid-Portion Achilles Tendinopathy and Paratendinopathy: Key Points

1	Controversy exists regarding the role of degenerative changes as the main cause of pain.
2	The plantaris tendon has been implicated in the pathophysiology as part of a frictional syndrome.
3	Eccentric-concentric loading protocols should be considered, since there is little evidence for isolating the eccentric component.
4	Injection of a dilute anaesthetic into the tendon sheath to break up adhesions can be used to treat Achilles paratendinopathy.
5	Achilles tendoscopy can be used to release adhesions, denervate the tendon, remove of pathologic tissue, and release of the plantaris tendon.

Mid-Portion Achilles Tendinopathy and Paratendinopathy: Key Points

This clinical syndrome is characterized by pain and swelling, which can be localized or diffuse, between 2 and 7 cm from the calcaneal insertion, causing impaired performance [23]. In any field of Achilles pathology, careful and systematic clinical evaluation is mandatory (Figure 4).

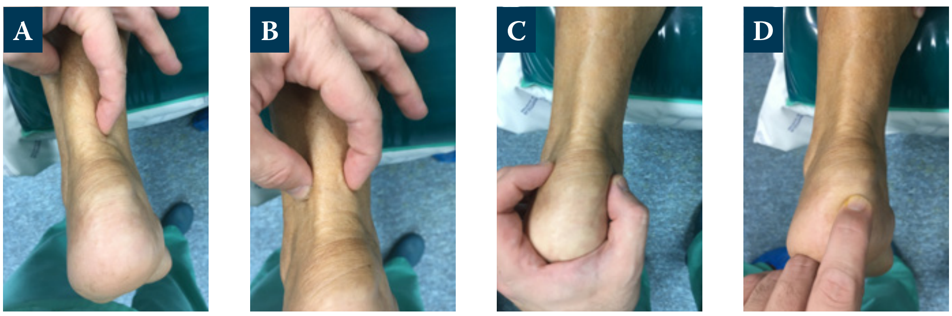

FIGURE 4 | Systematic palpation of different zones during Achilles clinical evaluation.

In this disorder only the tendon proper is affected. Histopathological diagnosis are not limited to tendinosis and it should be noted that the fundamental lesion of tendinopathy is failed healing response [23]. Controversy exists regarding the role of degenerative changes as the main cause of pain – with some authors believing that the tendon proper is not the source of pain in the majority of patients –, because up to 34% of asymptomatic tendons show histopathological changes [60]. However, tendons do seem to heal poorly, possibly on account of low tissue turnover. Heinemeier and colleagues found that the levels of 14C retained by Achilles tendon tissue corresponded to the atmospheric levels several decades before tissue sampling took place, indicating very limited tissue turnover [32]. The plantaris tendon (Figure 5) has also been implicated in the pathophysiology of mid-portion Achilles tendinopathy, as a part of a frictional syndrome between these two structures [11, 61].

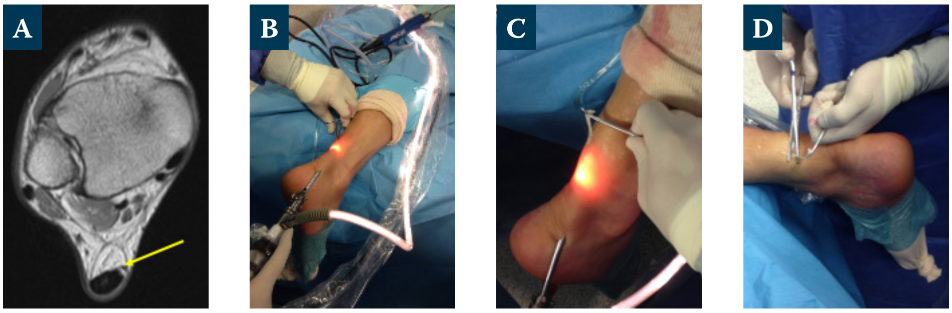

FIGURE 5 | A: MRI with visible plantaris tendon (yellow arrow). B to D: tendoscopy of the Achilles with detachment and removal of the plantaris tendon.

Treatment for non-insertional Achilles tendinopathy is largely conservative. Initial rest, modification of training regimes, specific exercises and correction of underlying lower limb alignment issues with orthotics are some of the treatment modalities. Most patients will be able to return to previous activities: in an eight-year follow-up study only 29% failed to respond adequately to non-operative management [47].

Eccentric strength training is commonly regarded as a key element in the treatment of this disorder. However, in a systematic review comparing clinical outcomes and identifying potential mechanisms for effectiveness of Achilles and patellar tendinopathy loading programmes, Malliaras and colleagues have shown that there is little clinical or mechanistic evidence for isolating the eccentric component [42]. They recommended that eccentric-concentric loading should be considered, along with or as a substitute of eccentric loading alone. The use of customized foot orthotics has also been disputed, as these seem to be no more effective than sham foot orthotics in patients undergoing an eccentric exercise programme [44].

Injection therapies may also be effective treatments. From a literature review it has been asserted that ultrasound-guided dry needling with high-volume injection provides good short-to medium-term relief of symptoms in the management of chronic mid-substance Achilles tendinopathy. Platelet-rich plasma (PRP) injections may also deliver good overall results, with a stable outcome at medium and long-term follow-up [26, 27, 30], but these seem to be less effective on aged patients [57]. However, the efficacy of these treatments has been disputed [70, 71]. The stromal vascular fraction extracted from adipose tissue can also be safe and effective in the treatment of recalcitrant Achilles tendinopathy, with the additional benefit of offering a faster recovery when compared with PRP [66]. Paratendinous injections of autologous blood are of no benefit when administered in combination with an eccentric training programme [7].

In veterinary medicine, stem cells have been used with encouraging results in the treatment of the superficial digital flexor tendinopathy in horses [45]. Results regarding its use in humans remain to be published, with clinical trials currently underway to assess the safety and efficacy of autologous stem cells in the treatment of Achilles tendinopathy.

Conventional surgical treatments entail the release of adhesions, which may be combined with resection of the paratenon. If using an open approach, a longitudinal tenotomy can be performed and macroscopic areas of tendinopathic areas tissue removed. Additional multiple tenotomies can be performed to initiate vascular ingrowth and a healing process. Augmentation is recommended if more than 50% of the tendon has to be debrided [54]. Success rates for open surgery vary widely, but are generally reported as being between 75% and 100% [54]. Stripping of the paratenon is thought to be effective by removing the neovascularisation and denervate the diseased area of the tendon [60]. Gastrocnemius lengthening has also been advocated as potential treatment: Duthon et al treated 14 patients with this procedure and found that 79% were able to return to their previous sporting activities at two years' follow-up with repeat MRI scans showing significant improvements in tendon quality at one year [24]. Achilles tendoscopy can also be used, with good results, to achieve release of adhesions of the paratenon, denervation of the tendon, removal of pathologic peritendinous tissue, and endoscopic release of the plantaris tendon (Figure 5) [20, 50].

Achilles Paratendinopathy

Paratendinopathy is defined as inflammation, either acute or chronic, with or without degeneration, of the thin membrane surrounding the Achilles tendon [23]. Most important clinical features are pain induced by exercise and swelling around the mid-portion of the tendon. Acute cases will have swelling and crepitation, with the latter not being present in mid-portion Achilles tendinopathy. Swelling and crepitations will be less pronounced in chronic cases. Typically, in patients who have acute symptoms, the area of swelling and tenderness does not move when the ankle joint is dorsiflexed [46]. It should be noted that Achilles paratendinopathy frequently coexists with mid-portion tendinopathy.

Acute paratendinopathy will have a normal Achilles tendon with a circumferential hypoechogenic halo on ultrasound and a peripheral enhancement on fat-saturated T1 or on T2 images [19]. A thickened hypoechoic paratenon with poorly defined borders may show as a sign of peritendinous adhesions on chronic cases, which may be accompanied by an increase in tendon vascularity in the ventral peritendinous area [23].

Initial nonoperative management aims to identify and correct predisposing factors, similarly to what happens with tendinopathy cases. Brisement has proven to be helpful in treatment of paratendinopathy [65]. This procedure consists of taking a dilute anaesthetic and injecting it into the tendon sheath to break up adhesions.

If surgical treatment is warranted, an endoscopic approach can be used to attain release of adhesions and resection of the paratenon, similarly to what was described above for mid-portion Achilles tendinopathy [20]. A literature review by Kriegelstein and colleagues showed excellent results for Achilles tenoscopy in the treatment of pathologies of the paratenon and Achilles tendinopathy [38].

Insertional Achilles Tendinopathy

This is a condition affecting the calcaneal insertion of the Achilles tendon, and may be accompanied by the formation of bone spurs and calcifications in this area [23]. Clinically, there is pain on palpation at the tendon insertion, swelling may be present, and a bony spur may be palpable. This disorder tends to affect more active persons, in contrast with non-insertional tendinopathy which tends to affect older, less active and overweight patients [35]. An epidemiologic study in non-athletes and found Achilles tendinopathy in 5.6% of the patients, with 4% being insertional and 1.9% being both insertional and non-insertional [67].

The causes of insertional Achilles tendinopathy (Table 2) can be divided into intrinsic and extrinsic risk factors. Intrinsic risk factors include structural or biomechanical foot, ankle, and lower extremity conditions. Common extrinsic factors, although anecdotal and lacking scientific evidence, are: overtraining, improper stretching/preparation, shoe gear, obesity, age, and mechanical overload [13].

TABLE 2 | Insertional Achilles Tendinopathy: Key Points

1	Low-energy extracorporeal shock wave therapy is an effective treatment that shows superior results when combined with eccentric loading.
2	A postero-lateral approach can be used to perform surgical debridement and reinsertion of the Achilles tendon.
3	Double-row constructs have a larger contact area and significantly higher peak load to failure compared with single-row constructs.
4	Knotless suture bridge repairs may have a lower load to failure than the knotted version.
5	Augmentation with flexor hallucis longus transfers may not be strictly needed in primary cases in older patients.

Insertional Achilles Tendinopathy: Key Points

Evidence provided by several studies suggests that the calcification seen in these individuals is related to stress shielding forces [8, 41, 56]. This adaptation increases the surface area at the bone-tendon junction, thereby protecting this area from increased mechanical loads.

Several non-operative treatment modalities have been proposed, including eccentric stretching and strength training and heel lifts. According to a systematic review by Al-Abbad and Simon, there is satisfactory evidence that low-energy extracorporeal shock wave therapy (ESWT) is an effective treatment in chronic insertional and non-insertional Achilles tendinopathy at a minimum of 3 months' follow-up [4]. However, combining ESWT with eccentric loading appears to show superior results. Platelet-rich plasma and high molecular weight hyaluronic acid injections have also been shown to be beneficial in insertional Achilles tendinopathy [25, 39], but evidence is scarce. Factors correlated with failing of non-operative treatment are: visual analog scale greater than 4, limited ankle range of motion, previous corticosteroid injection, and presence of Achilles tendon spurs; as the number of risk factors increases so does the chance of failing non-operative treatment: with all 4 parameters, the probability of failing conservative treatment is 55% [59].

When conservative measures fail, surgical treatment is indicated (Figure 6). This can be achieved through a central incision with complete detachment of the Achilles tendon, debridement of diseased tissue, removal of spurs and reattachment with the suture bridge technique. This provides an effective treatment with good to excellent clinical outcomes in 97% of patients, with a mean follow-up of 29 months [29]. A postero-lateral approach can also be used, instead of approaching the insertion through a midline incision, which can be advantageous because more superficial fibers tend to be uninvolved [33]. The Achilles tendon can be elevated from lateral do medial and proximal to distal. This technique preserves some of the insertion and allows up to 50% of the tendon to be resected safely.

Double-row constructs for reinsertion of a completely detached Achilles tendon using proximal and distal rows results in significantly larger contact area and significantly higher peak load to failure on destructive testing (Figure 6) [6]. A cadaveric biomechanical study demonstrated that the knotless suture bridge repair had a significantly lower load to failure than the knotted suture bridge [16].

FIGURE 6 | A: MRI changes with visible insertional tendinopathy and big calcifications.

FIGURE 6 | B: Open Approach of the Achilles.

Achilles insertional tendinopathy surgery results in few complications with good functional results if the surgical technique is adapted to the type of tendon injury [55]. According to a study by Rigby and colleagues, complications include postoperative wound dehiscence requiring surgical debridement (5%) and soft tissue infection requiring antibiotics and surgical debridement (2%) [53]. McAlister and Hyer also found a low reoperation rate in their series of midline approach with Achilles detachment and reinsertion [43].

Flexor hallucis longus transfer can be used safely to supplement Achilles tendon debridement and exostectomy in older patients, but may not be strictly needed in primary cases [34]. When augmentation is felt to be needed, bone-quadriceps tendon grafting is also a good alternative for the insertional Achilles lesions with partial detachment [51].

In patients with non-insertional Achilles tendinopathy and a gastrocnemius contracture that persists despite an eccentric stretching program being used, proximal medial gastrocnemius release is another viable option. This procedure can be done as an outpatient procedure that is well tolerated and without wound healing concerns due to the proximally based incision. These patients can expect notable improvement, with VISA-A scores possibly normalizing after the procedure [31, 63].

Retrocalcaneal Bursitis

This disorder is defined as an inflammation of the bursa in the retrocalcaneal recess, which is located between the anterior inferior side of the Achilles tendon and the postero-superior facet of the calcaneus [23]. This manifests as a visible and painful soft tissue swelling, on the medial and lateral sides of Achilles tendon at the same level of the postero-superior calcaneus (Table 3).

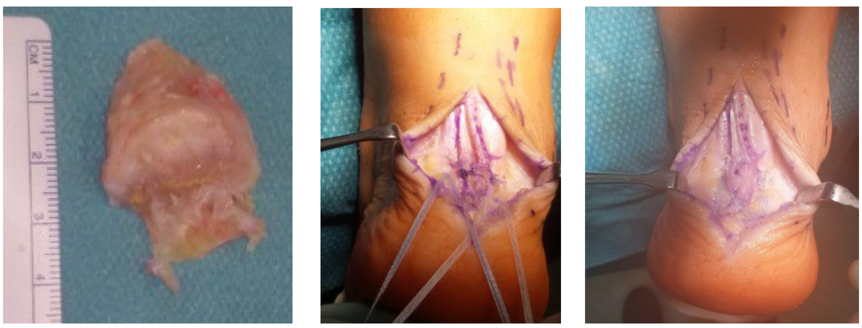

FIGURE 6 | C: Tendon detachment, debridment, removal of calcifications, calcaneoplasty and re-insertion by means of double row anchors.

TABLE 3 | Retrocalcaneal and Superficial Calcaneal Bursitis: Key Points

1	There is no correlation between prominence dimension and symptoms.
2	A lateral view in plain digital radiographs can be used to diagnose this condition but cannot be used as a reliable diagnostic criterion in patients who previously underwent endoscopic calcaneoplasty.
3	Corticosteroid injections should be avoided because of there is a connection between the retrocalcaneal bursa and the anterior fibers of the Achilles tendon.
4	Currently accepted treatments include endoscopic calcaneoplasty, percutaneous resection of the postero-superior tuberosity and Zadek osteotomy.
5	Superficial calcaneal bursitis happens without involvement of the Achilles tendon and this bursa is acquired after birth as a response to friction

Retrocalcaneal and Superficial Calcaneal Bursitis: Key Points

It is common to find an increased prominence of the posterior superior tuberosity on plain radiography, but there is no correlation between prominence dimension and symptoms [21]. Patients with prominent posterior superior calcaneal tuberosities can stay asymptomatic all life, and patients with a normal calcaneus can have recalcitrant symptoms. Patients with hindfoot varus and cavus foot have a higher predisposition for this disorder [10, 21].

Repeated dorsiflexion of the ankle pushes the Achilles tendon anteriorly, compressing the bursa against the calcaneus. Some cases can happen in conjunction with insertional Achilles tendinopathy [3]. This condition is often of idiopathic origin but can also be due to inflammatory arthropathy or infection.

This condition can be diagnosed with an MRI or an X-ray. Kager's triangle will be appearing clearer in the lateral view in plain digital radiographs [62]. However, the appearance of the retrocalcaneal recess on a lateral radiograph cannot be used as a reliable diagnostic criterion in patients who previously underwent endoscopic calcaneoplasty (Figure 7) [69].

FIGURE 7 | Endoscopic calcaneoplasty approach.

Conservative treatment includes multiple physical therapy protocols. Shoe changes or modifications can also produce positive effects, especially in athletes during the competitive season. Corticosteroid injections should be avoided in retrocalcaneal bursitis because of a connection between the retrocalcaneal bursa and the anterior fibers of the Achilles tendon, which puts the tendon at risk of rupture [64].

Several surgical treatments have been proposed with similar success rates [68]. Currently accepted treatments include endoscopic calcaneoplasty and dorsal wedge or Zadek osteotomy. Both can be done with good results in athletes, with endoscopic calcaneoplasty apparently enabling a faster return to activity: 6 to 12 weeks versus 3 to 7 months [22, 28]. A minimally invasive percutaneous approach can also be used to resect the postero-superior tuberosity of the calcaneus, as described by Mariano de Prado [52]. When retrocalcaneal bursitis and insertional Achilles tendinopathy coexist, the use of the central tendon-splitting approach appears to be safe and satisfactory [3].

Superficial Calcaneal Bursitis

This disorder (Table 3) is defined as an inflammation of an adventitious bursa between the posterior aspect of the calcaneus or Achilles tendon and surrounding skin [23]. This usually happens without involvement of the Achilles tendon. This bursa is acquired after birth as a response to friction, being frequently associated with a rigid shoe counter or poorly fitting shoes [48]. The athletes must be particularly careful with the choice of the adequate shoes and equipment.

Most patients with microtraumatic superficial bursitis respond to conservative management, which includes: ice, elevation, activity modification, appropriate padding, compression wraps, and over-the-counter analgesics [37].

Achilles Rupture

The rupture of the Achilles tendon, particularly in a high-level athlete, is a serious condition, and despite the positive outcome reported in all forms of treatment, from conservative, minimally invasive or open (Figure 8), it can lead to accelerating the end of competitive career [12]. Age and the athletes' expectations play a role in this setting [12].

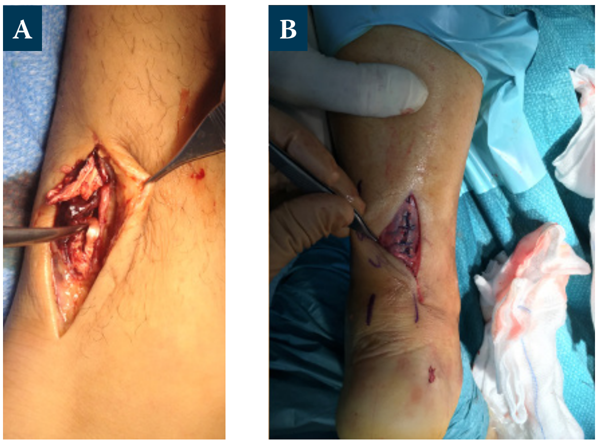

FIGURE 8 | A: Achilles tendon rupture. B: Open repair.

Achilles tendon ruptures are usually severe injuries in athletes, with return-to-sports rates around 70% and the risk for lowering performance post-injury must be considered [12]. In athletes there is a global trend in favour of surgical treatment, since conservative treatment has been linked to some loss of function and force [12].

More recently we have seen several advances in this field, including minimally invasive approaches such as the endoscopic transfer of the *flexor hallucis longus* tendon (Figure 9), promising to enhance the biology repair with minimal comorbidities and faster return to activity [5].

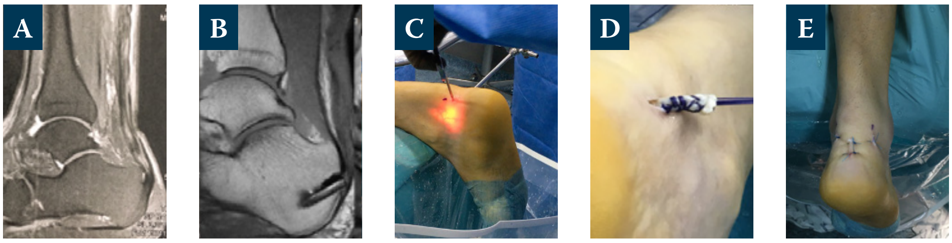

FIGURE 9 | A: MRI showing complex Achilles rupture. B: MRI after Flexor Hallucis Longus Transfer (FHL). C: Endoscopic approach. D: the harvested FHL retrieved on the endoscopic portal. E: Final external look of the three portal technique for FHL endoscopic transfer.

PRINCIPLES OF PREVENTION AND REHABILITATION

One of the fields which has suffered higher development in sports science is monitoring the individual's physical condition. Despite some external factors related to the shoe wear, training conditions, specificities of individual sports disciplines, understanding in each moment the global fatigue level of the athlete and his recovery capacity from the implemented training program is critical to lower the injury risk [1, 12].

However, we must assume that, at the moment, there is no effective way to predict which athlete presents higher risk for Achilles pathology, besides those linked with anatomic intrinsic factors such as poor gastrocnemius-soleus flexibility, overpronation, overweight, inflammatory diseases or extrinsic factors like sudden increase in training intensity, change in running /training surface, worn out or inappropriate footwear or medications (quinolones, statins) [1].

Concerning conservative treatment of several pathologies, shock wave therapy, percutaneous intra-tissue electrolysis and biologics have been increasing its relevance [1].

Elongation of posterior chains to increase gastrocnemius-soleus flexibility (Figure 10), neuromuscular training to improve proprioception (Figure 11) and strengthening exercises (Figure 12), adequate to the involved discipline are of paramount relevance in either prevention and rehabilitation programs [1, 2, 12].

FIGURE 10 | A to C: Exercises for posterior chain exercises flexibility.

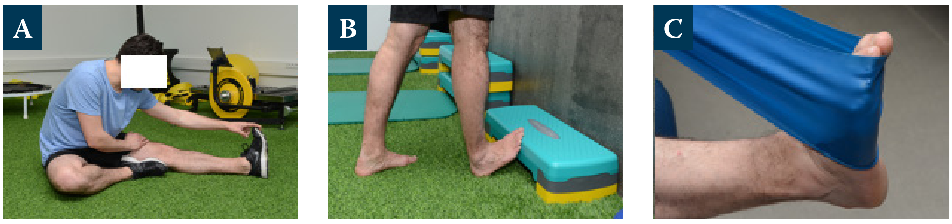

FIGURE 11 | A and B: Neuromuscular and proprioception training.

FIGURE 12 | A: Combination of strengthening and proprioception exercises. B and C: Gastrocnemius strengthening.

CONCLUSION

Complaints related to the Achilles tendon can be the result of one or more disorders. These are very frequent in Athletes from all disciplines and adequate diagnosis is mandatory for a good outcome. There tends to be confusion regarding the correct terminology of these entities with some descriptions being sometimes used erroneously. Treatment of these disorders is largely conservative. If surgical treatment is indicated, many technical options are described in the literature.

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Section Beta

Using finite element modeling to study risk factors for Achilles tendon ruptures

Chapter 3: Design and validation of a finite element model of the aponeurotic and free Achilles tendon

Chapter 4: Does free tendon length influence the injury risk of the Achilles tendon? A finite element study

Chapter 5: Progression of partial to complete ruptures of the Achilles tendon during rehabilitation: a study using a finite element model

CHAPTER 3

Design and validation of a finite element model of the aponeurotic and free Achilles tendon

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INTRODUCTION

The Achilles tendon (AT) is the tendon of the triceps surae muscle complex, and it is made from the confluence of the soleus and gastrocnemius subtendons [32]. These subtendons start as independent muscle aponeuroses [30], joining at approximately 38-43% of the distance from the calcaneal insertion to the fibular head [16].

The AT is approximately 15-20 cm long and starts at the gastrocnemius and soleus muscles' myotendinous junction (MTJ) [32]. It can be divided into an aponeurotic region, from the distal gastrocnemius MTJ to the distal soleus MTJ, and a free tendon region, from the distal soleus MTJ to the calcaneal insertion. The free tendon is serially connected to the aponeurotic component, which connects to the muscle fascicles in a broad region [24]. The length of the free tendon is, on average, 5.51 cm [37]. Fascicles from the soleus muscle insert anteriorly in the aponeurotic AT. The soleus, a multipennate muscle [1], provides most of the force exerted by the triceps surae complex [27], and it is divided into posterior, anterior, and marginal (medial and lateral) portions [1].

The soleus and gastrocnemius subtendons twist around each other before inserting into the calcaneus [12], and can to some degree slide independently [22]. In a left limb, the twist is in the clockwise direction, from a superior view, and in a right limb, it is in a counter-clockwise direction [14]. Several patterns of twisting have been described in the literature [12, 14], and are commonly grouped into small, moderate, or large twisting [12, 14], with some authors reporting values ranging from 30 to 150 degrees [43]. This twisting is more pronounced in the distal 5-6 cm of the AT [7].

Despite its large size and biomechanical features, the AT is a common site of injury. Ruptures are commonly considered to occur 2-6 cm from the calcaneal insertion [40]. However, a study by Park and colleagues [36] has shown that most of these injuries are located 5-8 cm above the calcaneal insertion, with the mean distance being 6.4 cm, which is farther from the calcaneal insertion than the average free tendon length. Ruptures may also be, although less frequently, located in the distal soleus MTJ [2].

Several computational models have been developed to study the influence of functional [21, 22, 28, 47], geometrical [50], and material features [23, 46, 48] on the AT biomechanical behavior. Limitations of these studies include no modeling of the aponeurotic AT or MTJ [21–23, 46–48], no implementation of subtendon sliding or fiber rotation [23, 28, 48, 50], and no comparison with experimental data [28, 50]. All the studies referenced included at least one of the aforementioned limitations and no study modeling subtendon sliding included the AT aponeurotic region.

Considering the possibility of aponeurotic region involvement in Achilles tendon ruptures, a computational model including both the aponeurotic and free tendon is of great interest. This study presents a 3D finite element model that includes both the aponeurotic and free AT regions and features subtendon twisting and sliding with the intent of testing two hypotheses: (1) that the model would be able to predict in vivo data collected from the literature, thus being considered valid, and (2) that, among the different geometrical and material conditions considered, the subtendon twist configuration would be the most relevant for the model outputs. This model is intended to be used in further biomechanical investigations of the Achilles tendon.

METHODS

Participant and image acquisition

A 34-year-old male (height: 180 cm; mass: 77 kg), healthy and recreationally active, with no previous injury to the Achilles tendon, was subjected to magnetic resonance imaging (MRI) of his left ankle. The imaging sequences were captured using a 1.5T MRI machine (Siemens Magnetom Aera 1.5T, Siemens) and included T2*-FS sagittal scans (repetition time 6.34 ms/echo time 2.54 ms; field of view (FOV), 240 mm; matrix 0.8 x 0.8 x 2 mm, 320 x 320 pixels; slice thickness, 2 mm; and 20% distance factor) and T1 vibe Q FS axial scans (repetition time 8.05 ms/echo time 2.54 ms; FOV, 240 mm; matrix 0.8 x 0.8 x 1 mm, 320 x 320 pixels; slice thickness, 1 mm; and 20% distance factor). Images were acquired in the supine position with the ankle at 90 degrees and the knee at 0 degrees. The soleus muscle's thickness in the calf's middle was measured using ultrasonography to estimate the soleus muscle volume using the formula described by Bandholm and colleagues [6]. An experienced radiologist excluded pathological changes in the Achilles tendon and soleus muscle.

Finite element model

Geometric model

Considering a previously described software pipeline for 3D solid and finite element (FE) modeling of biomechanical structures [41], the DICOM images were imported into a manual and semi-automatic segmentation software called ITK-SNAP [51]. The Achilles tendon and the distal part of the soleus muscle were segmented and exported as .STL files. The software MeshLab was used to simplify and smooth the geometric models [10], and Autodesk Fusion 360 (Autodesk Inc., San Rafael, CA, USA) was used to split the AT model into the gastrocnemius and soleus subtendons, as illustrated in Figure 13, using previously described anatomical studies for guidance [14, 15]. In this model, a moderate degree of twisting, as described by Edama et al. [14], was implemented, meaning that the gastrocnemius subtendon attached to the lateral half and the soleus subtendon onto the medial half of the calcaneal enthesis. A model of the distal soleus muscle was also created and used for muscle volume calculation and estimation of muscle fiber directions (Figure 13).

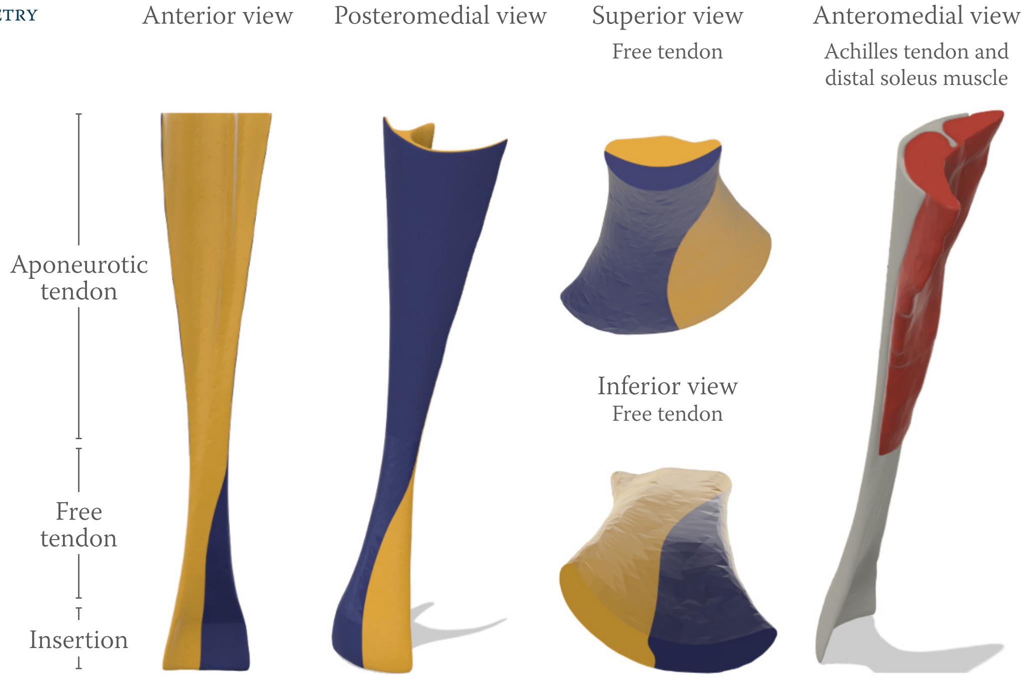


FIGURE 13 | MODEL GEOMETRY
Anterior view.
Posteromedial view.
Free tendon, superior view.
Free tendon, inferior view.

The resulting AT parts were imported into Abaqus 6.14 (Dassault Systèmes, Waltham, MA, USA) for the generation of a 3D FE model. All structures were meshed using hybrid quadratic tetrahedral elements (C3D10H). Mesh density was based on a sensitivity analysis, as detailed later.

Material model

The AT was represented as a transversely isotropic hyperelastic material, similar to what has been done in previous studies related to the FE analysis of the AT [22, 23, 28, 46–48, 50], using the constitutive model proposed by Gasser et al. [19]. In this model, the strain energy function $\overline{\Psi}$ for an incompressible material is represented as:

$$\overline{\Psi} = \begin{cases} C_{10}(\bar{I}_1 - 3) & \bar{I}_4 < 1 \\ C_{10}(\bar{I}_1 - 3) + \frac{k_1}{2k_2}\left(e^{k_2(k(\bar{I}_1-3)+(1-3k)(\bar{I}_4-1))^2} - 1\right)' & \bar{I}_4 \geq 1' \end{cases} \quad (1)$$

where C_{10}, k_1, k_2 and k are material parameters, $\bar{I}_1$ is the first deviatoric strain invariant, and $\bar{I}_4$ is the fourth deviatoric strain invariant. The parameter C_{10} defines matrix stiffness, k_1 defines a stress-like parameter related to fiber stiffness, k_2 defines a dimensionless parameter related to the nonlinear behavior of fibers, and k defines the level of dispersion of the collagen fiber orientations in the applied constitutive model [19]. This last parameter varies between 0 when fibers are perfectly aligned, i.e., when no dispersion exists, and 1/3 when fibers are randomly distributed, making the material isotropic.

Fiber directions were estimated using the method proposed by Choi and Blemker [9]. This method uses the Laplace equation to estimate fiber directions. In practice, an heat flux simulation was conducted on each of the subtendons, and a mapping procedure was used to transfer the fiber directions to the finite element mesh of the AT model.

Excluding the parameter k, the constitutive parameters were obtained by fitting the material model to experimental data of cadaveric ATs reported by Shim et al. [46]. The fitting problem was solved using the nonlinear least square algorithm *lsqcurvefit* of MATLAB R2019a (Math Works, Natick, MA, USA). Convergence to the same solution was found for 100 randomly generated initial sets of values, thus providing confidence that a global minimum was found [38]. Finally, the parameter k was measured experimentally by Kadlowec et al. [25] from the supraspinatus tendon using polarized light images and used here because no data specific to the AT was found.

Loading, boundary conditions, and interactions

Considering the in vivo experiments of Obst et al. [34] and Stenroth et al. [49] as reference for model validation, the FE model simulated an isometric plantarflexion contraction with the ankle in a neutral position. Force magnitudes used in each validation procedure were calculated from torque measurements, or reaction forces, reported in the corresponding in vivo study and based on moment arm calculations, as presented by Rugg and colleagues [44]. Moment arm was measured as the perpendicular distance between the joint center of rotation and a line along the direction of the tendon on sagittal plane MRI scans, and measured as 0.047 m. The triceps surae muscle was assumed to be responsible for 83% of the plantarflexion [17]. Loads were distributed in a 62%, 26%, and 12% proportion relative to the soleus, medial gastrocnemius, and lateral gastrocnemius, respectively, according to each muscle's physiological cross-section area, as determined by Albracht and colleagues [3].

The total and distal soleus muscle volumes were determined to define the percentage of force exerted by the distal soleus muscle. The volume measured from the segmented distal soleus muscle was 18.21 cm^3. The Bandholm equation estimated that the total soleus muscle volume was 322.72 cm^3 (soleus muscle thickness = 2.2 cm; lower leg length = 42 cm). Thus, it was assumed that the distal portion of the soleus corresponded to 5.64% of the total soleus muscle volume. Using data from Kinugasa et al. [27] it was estimated that, during contraction, this distal portion corresponded to 6.52% of the activated soleus muscle. This value was kept constant for all simulations.

Loads were applied on the most proximal cross-section and the anterior surface of the tendon. Since the gastrocnemius muscles' distal MTJs were not imaged, proximal force vectors were defined using mean fiber directions in the proximal aponeurotic tendon. The same was done for the proximal portion of the soleus muscle. These directions were confirmed to be similar to anatomic depictions found in the literature [13] and another FE study [48]. Forces were applied as concentrated forces at attachment points located at the proximal surface centroids and uniformly distributed to these surfaces using coupling constraints [11].

The distal portion of the soleus muscle pulled on the anterior surface of the aponeurotic AT with force vectors calculated based on average pennation angles for the anterior, posterior, and marginal (medial and lateral) sections, as described by Agur and colleagues [1]. These values are also consistent with previously reported values of pennation angles in a maximum voluntary isometric contraction (MVIC) with the ankle in the neutral position [29]. A user subroutine was developed in MATLAB to distribute the force exerted by the distal soleus muscle as individual concentrated forces, applied at each node in the anterior surface of the aponeurotic tendon (Figure 14). For each node, force vectors were computed in the following way: an interpolation procedure was used to pair that node with a node in the anterior surface of the soleus muscle model; from each pair of nodal coordinates, a vector was defined; a rotation axis was calculated from the cross product of this vector and the vector defining local material orientation; finally, the local material orientation was rotated about the rotation axis previously determined to match the intended pennation angle [1].

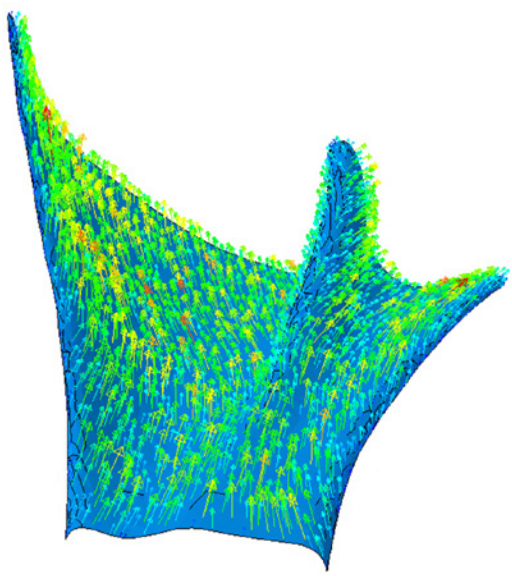


FIGURE 14 | CONCENTRATED FORCES IN THE ANTERIOR SURFACE OF THE APONEUROTIC TENDON
Loads corresponding to the distal soleus muscle pulling on the anterior surface of the aponeurotic tendon.

The AT insertion was fixed in the x, y, and z directions to prevent rigid body motion. The proximal surfaces of the tendon were constrained to move only along the direction of the force applied to them (Figure 15). The interface between the subtendons was modeled assuming a frictionless contact formulation without separation. Allowing subtendon sliding has been previously stated as necessary to adequately model displacements in the free tendon [22]. Since, to the authors' knowledge, no *in vivo* data quantifying friction between subtendons has been published, a frictionless behavior was assumed, similarly to what has been previously reported by other research groups [21, 22, 47]. Two other contact conditions were also modeled to evaluate the influence of interface behavior on the AT biomechanics: sliding with anisotropic friction and no sliding. No relative movement could exist at the interface in the no sliding condition, simulating a rigidly tied interface. In the anisotropic friction condition, a friction coefficient of 1 was arbitrarily defined for the transverse direction and 0 for the longitudinal direction, with the intent of allowing subtendons to slide longitudinally while providing some resistance against the relative movement in the transverse direction. Thus, for baseline models, three contact formulations were used: (i) no sliding, (ii) frictionless, and (iii) anisotropic friction.

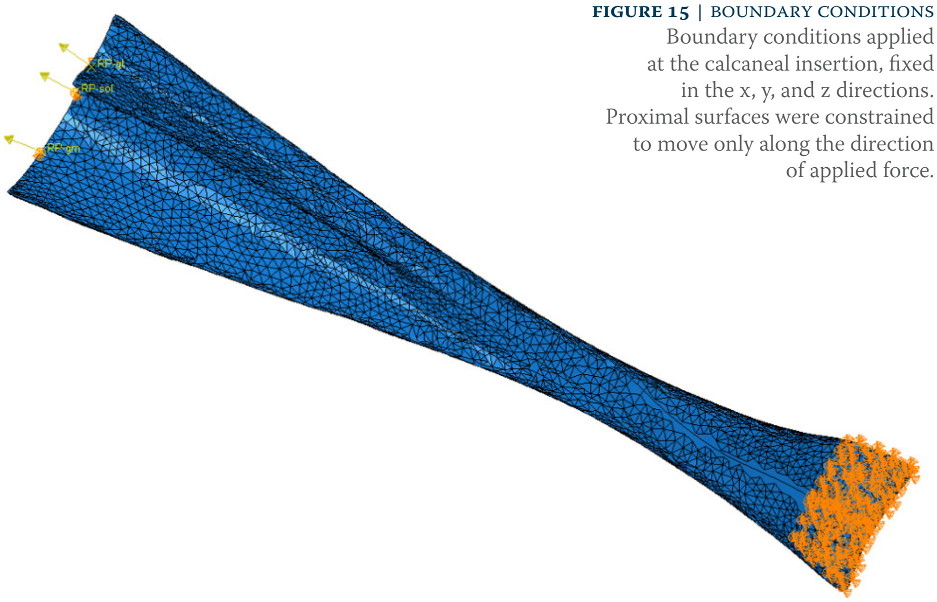


FIGURE 15 | BOUNDARY CONDITIONS
Boundary conditions applied at the calcaneal insertion, fixed in the x, y, and z directions. Proximal surfaces were constrained to move only along the direction of applied force.

Mesh convergence analysis

A mesh convergence study was entailed to find the optimum element size for subsequent analyses. In this step, the element size was progressively increased, and the displacements for several geometry-based nodes were compared between the smallest element size mesh (of 0.5 mm) and the mesh being studied. A maximum mean relative error of 1% in relation to the smallest element size was considered acceptable.

Model validation

Data from two studies reporting in vivo experiments [34, 49] were used for independent model validation. Graphical data were extracted using WebPlotDigitizer [4]. The model was considered valid for the parameter being evaluated when outputs were within one standard deviation of the mean values found in *in vivo* results [20, 22].

Free tendon three-dimensional deformation and transverse plane rotation

In a study by Obst and colleagues [34], 3D ultrasound was used to measure longitudinal strain and changes in the cross-section area (CSA), mediolateral diameter (MLD), anteroposterior diameter (APD), and transverse plane rotation in the free tendon. Eight subjects (all males, aged 28 ± 2.4 years) were asked to perform 70% MVIC in 15 degrees of plantarflexion, generating an average torque of 71.6 ± 21.3 N·m.

Considering the moment arm calculation and load distributions described above, a load of 1264.43 N was used in the simulation. To compare computational estimations of the developed FE models with those presented by Obst et al. [34], a point cloud of nodal coordinates comprising the model's free tendon was post-processed in MATLAB using a similar methodology to the one described by the authors. Briefly, cross-section centroids were calculated in 10% intervals of a straight line from 0 (calcaneal insertion) to 100% (distal MTJ) of the free tendon. Then, a cubic spline connecting each centroid was created. The longitudinal strain was calculated by subtraction of the length of the free tendon region at rest from the length of the same region under load and dividing this difference by the length of the free tendon region at rest. For CSA, MLD, and APD measurements, cross-section planes were defined by a normal vector tangential to the longitudinal spline at the cross-section centroid and centered at this point. Both MLD and APDs were calculated as distances between intersections of the moment of inertia axes and the cross-section boundary. Transverse plane rotation was calculated by measuring the angle between the mediolateral principal axis of the cross-section corresponding to the calcaneal insertion and the remainder cross-sections, with a negative value signifying external rotation.

Free tendon sagittal and coronal nodal displacements

Stenroth and colleagues [49] used an ultrasound speckle tracking algorithm to measure tissue displacements in the free tendon. Fourteen subjects (five females and nine males, aged 26 ± 3 years) performed maximal isometric ankle plantarflexion contractions with the knee extended and flexed to 110 degrees. Six tissue regions of 16 uniformly spaced nodes each were defined across a 15-mm-long tendon section, located distal to the MTJ in the sagittal and coronal planes. For each patient, peak nodal displacements across trials were averaged for each region, and regional displacements were normalized by dividing the average displacement in each region by the average displacement across all regions.

Using the same aforementioned moment arm calculation and load distributions, a load of 1786.41 N was used in this simulation. Using a post-processing script in MATLAB, nodal displacements in a 15-mm-long section located distal to the MTJ were calculated. Nodal coordinates in the undeformed condition were used to bin nodes into six regions. Regions were limited by seven planes, equally spaced and perpendicular to the sagittal or coronal planes, depending on the evaluated parameter (See Appendix I). The sagittal and coronal planes were manually defined according to a schematic drawing found in the supplemental material file of the referenced paper [49]. Nodal displacements were then computed for each plane, averaged for each region, and finally normalized in the same manner as performed by Stenroth et al. [49]. Comparison with in vivo data was made using the results from the trial with the knee extended.

Summary of modeling parameters

Data related to model validation and subsequent FE simulations, including loads and material parameters, are summarized in Table 4.

TABLE 4 | MODEL PARAMETERS

MODEL	
Ankle MA [44] (mm)	47
TS PF force contribution [17]	83%
LOAD DISTRIBUTION [3] IN TS	
Soleus	62%
Medial Gastrocnemius	26%
Lateral Gastrocnemius	12%
LOADS (N)	
OBST ET AL. (2014) [34]	
70% MVIC	1264.43
STENROTH ET AL. (2019) [49]	
100% MVIC	1786.41
MATERIAL PARAMETERS	
C10	30.549
D	0
k1	327.345
k2	0.01
k [25]	0.139

Model parameters used in finite element analyses.
MA: moment arm.
MVIC: maximum voluntary isometric contraction.
PF: plantarflexion.
TS: triceps surae.

Sensitivity analyses on modeling conditions

Several sensitivity analyses were conducted to assess the influence of subtendon twist configurations, material model parameters, and tendon length (by limiting the model to the free tendon) on simulation outputs. FE simulations were performed considering the anisotropic friction model. The root mean square deviation (RMSD) between baseline and sensitivity models was computed for each simulation.

Regarding subtendon twisting, two additional models were created based on the description by Edama et al. [14], corresponding to the Types 1 (Least twisting) and 3 (Extreme twisting) of their classification. Details of these FE models can be found in Appendix I.

To assess the model sensitivity to changes in material parameters, each of the material parameters was increased or decreased by 25% while keeping the other parameters constant.

Finally, one last FE model comprising the free tendon only was developed to investigate subtendon sliding in the transverse direction in the free tendon region under similar conditions as those considered by previous computational models [22, 47]. In addition to the anisotropic friction condition, the frinctioless contact condition was also evaluated. Surface nodes in the baseline and free tendon-only models were paired by finding the closest pair of nodes in the tendon section common to both models, and slipping in the transverse direction was compared using the RMSD. For these comparisons, nodes close to boundary conditions were excluded under Saint Venant's principle [18].

Statistical analysis

Statistical analyses were performed using Microsoft Excel for Mac V16.45 (Microsoft Corporation, Redmond, WA, USA) and MATLAB. Descriptive statistics are represented as means and standard deviations, except where otherwise specified. One-way ANOVA was used to compare contact conditions and assess the main effect of tissue region on nodal displacements. In addition, Pearson's correlation coefficient was used to evaluate if nodal displacements increased linearly in the posterior-anterior or lateral-medial directions. Statistical significance was set at $p < 0.05$.

RESULTS

Finite element analysis and model validation

The AT model measured 17.72 cm in length. The free tendon measured 6.89 cm. The soleus and gastrocnemius subtendon volumes were 699.07 mm^3 (55.75%) and 554.82 mm^3 (44.25%), respectively. An element size of 0.9 mm was selected to save computational time while keeping the relative error acceptably low (<1%). Simulations required a mean of 4.02 ± 0.99 hours (range: 2.99 to 5.98) to converge.

Qualitatively, the frictionless contact model exhibited a noticeable medial transverse sliding of the soleus subtendon, which extended proximally from the subtendon twisting region to the aponeurotic region, regardless of the force magnitude applied. This finding was also present in the anisotropic friction model, albeit to a much lesser degree (Figure 16). In addition, all models exhibited widening and flattening of the aponeurotic region under load.

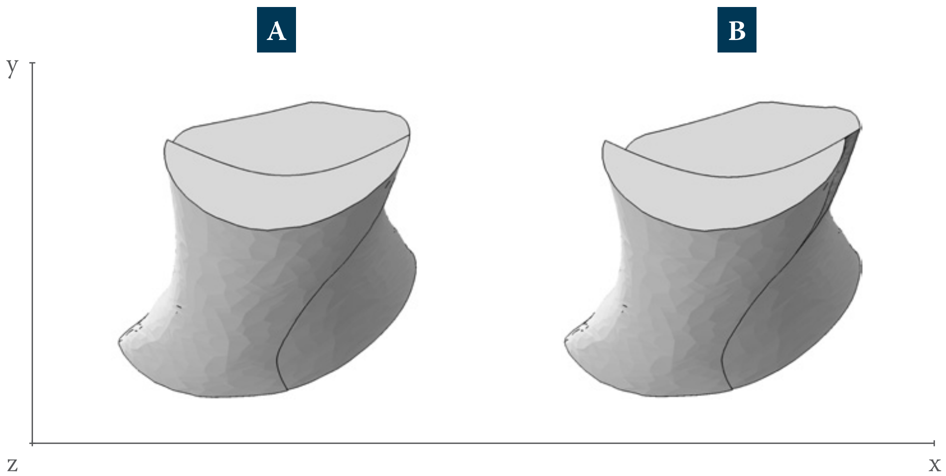


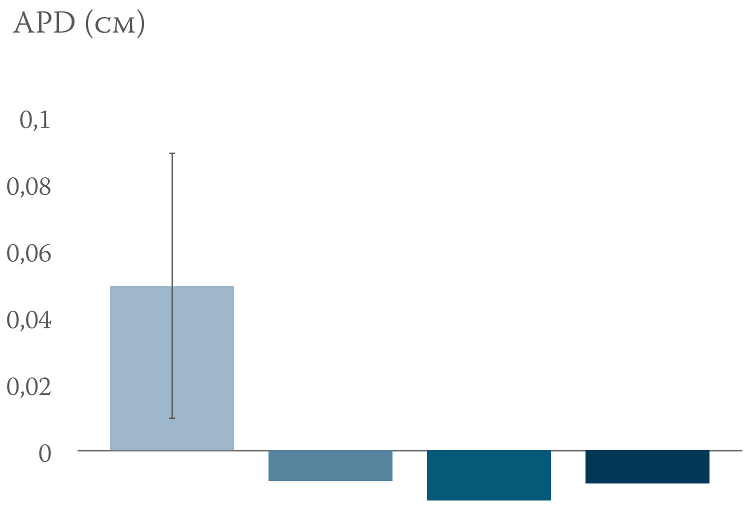
FIGURE 16 | TRANSVERSE SLIDING IN ANISOTROPIC FRICTION AND FRICTIONLESS MODELS
Free tendon section from superior view, under 1786.41 N load. A: anisotropic friction model. B: frictionless model.

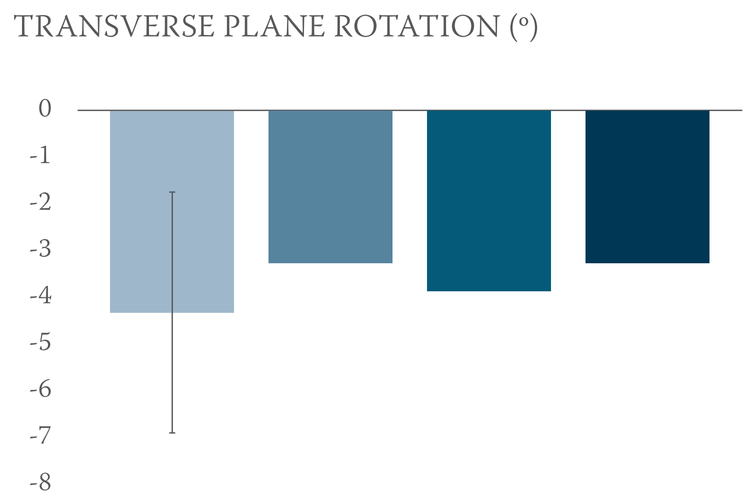
Free tendon three-dimensional deformation and transverse plane rotation

For the no sliding, anisotropic friction, and frictionless models, respectively, longitudinal strain was 3.04, 4.19%, and 4.37 (in vivo: 6.4 ± 3.1 %); mean changes in CSA were -0.02 cm^2 for all models (in vivo: -0.05 ± 0.04 cm^2); mean changes in MLD were -0.02 cm, -0.01 cm, and -0.003 (in vivo: -0.16 ± 0.07 cm); mean changes in APD were -0.01 cm for all models (in vivo: 0.05 ± 0.04 cm); and transverse plane rotation was -3.29, -3.33, and -3.91 degrees (in vivo: -4.36 ± 2.6 degrees). Figure 17 illustrates the simulation results and target values.

FIGURE 17 | FREE TENDON THREE-DIMENSIONAL DEFORMATION AND TRANSVERSE PLANE ROTATION
Comparison with in vivo data from Obst et al. [34].
CSA: cross-section area.
MLD: mediolateral diameter.
APD: anteroposterior diameter.
SD: standard deviation.

Target mean and SDs
No sliding
Frictionless
Anisotropic friction

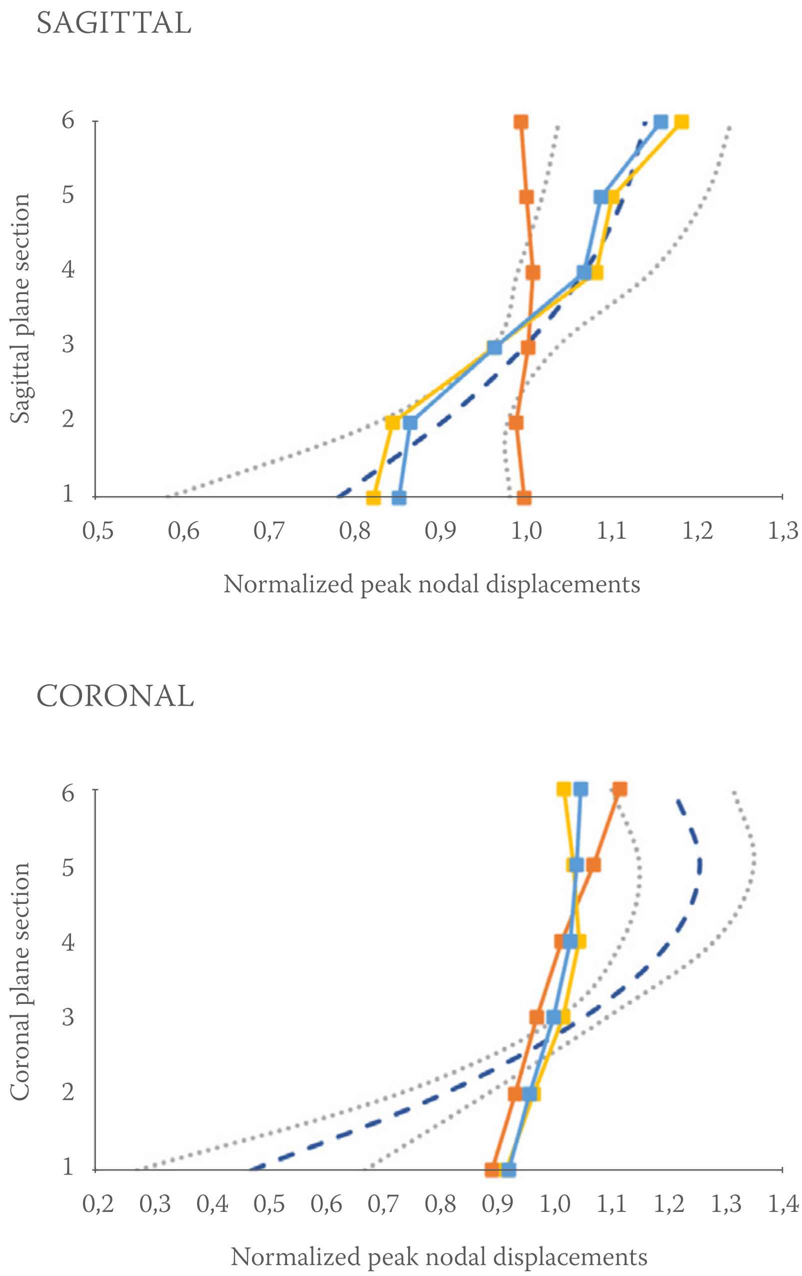




Free tendon sagittal and coronal nodal displacements

The effect of the region was statistically significant for all models in both the sagittal and coronal planes ($p < 0.05$). Sagittal nodal displacement increased from the posterior to anterior regions for the frictionless and anisotropic friction models, exhibiting a strong positive correlation ($r = 0.98$; $p < 0.05$). The no sliding model presented no correlation between the posterior-anterior regions and sagittal nodal displacement ($r = 0.15$; $p = 0.78$). Coronal plane displacements increased from the lateral to medial regions of the tendon for all models. Strong positive correlations, of 0.99 ($p < 0.05$), 0.96 ($p < 0.05$), and 0.81 ($p = 0.05$), were found for the no sliding, anisotropic friction, and frictionless models, respectively. Figure 18 compares estimated data with *in vivo* data.

FIGURE 18 | FREE TENDON SAGITTAL AND CORONAL NODAL DISPLACEMENTS
Comparison with in vivo data, peak nodal displacements during plantarflexion with an extended knee, from Stenroth et al. [49]. Values here represented are normalized nodal displacements. Y-axis: sections 1 to 6, where 1 is the most posterior section in the sagittal plane and the most lateral in the coronal plane.



Sensitivity analyses on modeling conditions

Overall, the model was most sensitive to changes in subtendon twist configuration. Regarding changes in material model parameters, the model was most sensitive to changes in the parameter k, followed by k_1 and C_{10}.

Model validity was not affected by varying the subtendon twist to Type 1 (Least twisting). For the Type 3 (Extreme twisting), the sagittal plane displacements deviated from the validation range. Results of subtendon twist variation models are detailed in Appendix I (Figures I-D to I-J). No changes in the validity of outputs were found related to variations in the material parameters. Detailed data related to these sensitivity analyses can be found in Table 5.

TABLE 5 | RESULTS OF SENSITIVITY ANALYSES

MODEL		LS	CSA (cm^2)	MLD (CM)	APD (CM)	ROTATION (°)	RMSD
BASELINE		4.1929	-0.0190	-0.0117	-0.0091	-3.3248	-
C10	+25%	3.9305	-0.0175	-0.0102	-0.0094	-3.0016	0.1862
	-25%	4.4579	-0.0204	-0.0100	-0.0086	-3.7404	0.2204
k1	+25%	3.6078	-0.0163	-0.0061	-0.0093	-3.2118	0.2665
	-25%	4.9937	-0.0228	-0.0155	-0.0098	-3.4696	0.3640
k2	+25%	4.1920	-0.0190	-0.0116	-0.0083	-3.3249	0.0005
	-25%	4.1975	-0.0190	-0.0116	-0.0084	-3.3249	0.0021
k	+25%	5.2173	-0.0241	-0.0176	-0.0114	-3.4992	0.4647
	-25%	3.3765	-0.0152	-0.0083	-0.0068	-3.1508	0.3733
EDAMA 1		3.9639	-0.0187	-0.0146	-0.0099	-5.6484	1.0442
EDAMA 3		6.3122	-0.022	-0.0202	-0.0078	-1.4135	1.2763

Values expressed as the variation between deformed and at rest conditions for a simulation using a load of 1264.43 N. LS: longitudinal strain. CSA: cross-section area. MLD: mediolateral diameter. APD: anteroposterior diameter. RMSD: root mean square deviation. Edama 1 corresponds to the Type 1 (Least twisting) of subtendon twisting as described by Edama et al. and Edama 3 to the Type 3 (Extreme twisting) of the same classification.[14]

Regarding transverse sliding of surface elements in the subtendon interface, RMSD between frictionless and anisotropic friction contact conditions in the free tendon only model was 0.05 mm, compared with 0.46 mm for the same region between the baseline frictionless and anisotropic friction models. Furthermore, no statistically significant differences were found between contact conditions (frictionless and anisotropic friction) in the free tendon-only model ($p = 0.0719$). The RMSD between the anisotropic friction baseline and frictionless free tendon only models was 0.076 mm, while the RMSD between the frictionless baseline and frictionless free tendon only models was 0.417 mm.

DISCUSSION

The objective of the present work was to develop an AT model including both aponeurotic and free tendon regions and test if the model could predict in vivo data collected from the literature, and if the subtendon twist configuration would be the most relevant for the model outputs among the different geometrical and material conditions considered. The AT finite element model developed was divided into the soleus and the gastrocnemius subtendons and was shown to adequately simulate the *in vivo* free tendon behavior regarding longitudinal strain, CSA variations, transverse plane rotation, and sagittal plane nodal displacements, provided that subtendon sliding was allowed. However, changes in MLD and APD, and coronal nodal displacements, were found not to be within one standard deviation from the mean of experimental data used in this study, regardless of the contact formulation used. The model was most sensitive to variations in subtendon twist configuration.

While investigating mechanisms underlying nonuniform tissue displacements, Handsfield and colleagues [22] concluded that differences in muscle forces and subtendon sliding had the most prominent role in displacement discrepancies across tendon regions. In their model, subtendon sliding was modeled as a frictionless contact interface. When this methodology was replicated in the whole tendon model presented here, noticeable transverse sliding, not present in a free tendon-only model, occurred. Thus, an anisotropic friction model was employed, based on the assumption that transverse sliding may be limited *in vivo* by the presence of the paratenon and fascia cruris. These two soft tissue layers merge at a mean of 37.3 mm from the posterior superior calcaneal tubercle and surround the AT and all distal posterior structures in the calf, respectively [8]. Subtendon sliding using an anisotropic formulation allowed for a better prediction of the AT in vivo behavior. Regardless of the contact formulation used, it should be noted that friction coefficients used were defined arbitrarily due to the lack of experimentally determined values. Future FE studies may aim to evaluate alternative contact formulations and improve the modeling of the inter-subtendon matrix.

In this study, a method to simulate distal soleus muscle forces acting on the aponeurotic AT was devised employing a user subroutine, which allowed individual specification of pennation angles for each soleus region. In a previous FE study, the soleus muscle pennation angle was shown to influence the mechanical behavior of the AT, specifically tendon bending during plantarflexion [28]. Furthermore, patients with unilateral symptomatic Achilles tendinopathy have decreased pennation angles in this muscle compared with the healthy limb [35]. This model is of interest to further study distal soleus muscle architecture's influence on the AT mechanical behavior.

Mean differences in longitudinal strain, CSA, and transverse plane rotation for the frictionless and anisotropic friction contact conditions were within one standard deviation of the in vivo data reported in the work of Obst et al. [34]. The no sliding contact condition met all the above criteria except for the longitudinal strain. However, none of the contact conditions produced changes in MLD and APD within one standard deviation of mean values found *in vivo*. The inability to match *in vivo* changes in these parameters might be due to differences in the post-processing of point cloud data, characteristics of the material model, subtendon contact formulation, forces, or differences in ankle position (since subjects in the *in vivo* study performed isometric contractions in 15 degrees plantarflexion, while the FE model simulated an isometric plantarflexion with the ankle in the neutral position). On the other hand, changes in MLD and APD obtained for the no sliding and anisotropic contact conditions were within the margin of error of the 3D ultrasound measurement method used in vivo regarding the lower range of values considered for validation [33, 34].

Both frictionless and anisotropic friction conditions, but not the no sliding condition, presented sagittal nodal displacements that fit the normalized values range from experimental data [49]. However, none of the models showed coronal nodal displacements that matched *in vivo* values, despite following a similar trend, *i.e.,* displacements were larger in the medial than the lateral region. As evidenced in the supplementary material file of the referenced paper, the results of these experiments were dependent on probe positioning, and considerable individual variation existed. While these may justify our results, another aspect needs to be considered. In our model, the AT was divided into two subtendons instead of three, similar to what was done in other FE studies [21, 47]. The force exerted by the medial gastrocnemius is more than twice the force exerted by the lateral gastrocnemius. Therefore, allowing the gastrocnemius subtendons to slide independently could improve the fit of model outputs to experimental data regarding this parameter.

The sensitivity analyses on subtendon twist configurations, material model parameters, and tendon length showed subtendon twist configuration to be the most relevant to the model outputs. Overall, the results of the two additional FE models varying in subtendon twist (shown in Figures I-D to I-J in Appendix I) were similar to the baseline model (Edama 2, Moderate twisting). In the Edama 3 (Extreme twisting model), results slightly deviated from the validation range (i.e., within one standard deviation of the mean values found *in vivo*) for sagittal plane displacements, which can be attributed to the relatively low prevalence of this variation (7% in the study by Edama et al.). These results are in line with those presented by Hansen et al., in which stress distributions from FE simulations, using subject-specific models of healthy tendons, were more sensitive to variations in tendon geometry than material properties [23], albeit these models did not employ subtendon division and were restricted to the free tendon region. Thus, imaging methods to assess subtendon twisting may be of interest for further biomechanical investigations and assessment of specific patterns of AT division and twisting as injury risk factors.

Among the material model parameters, the model was most sensitive to parameter k. Increased fiber dispersion led to a larger longitudinal strain, transverse plane deformation, and rotation in the model. Interestingly, loss of collagen fiber orientation is a notable feature of tendinopathy [26], and may thus play a significant role in the altered mechanical behavior of tendinopathic tendons. Since no material parameter data was found specific to different AT regions or subtendons, the same values were used for the whole model. In the specific case of the parameter k, data from the supraspinatus tendon was used, as data related to the AT could not be found. The subject of regional AT material properties is of considerable research interest. Experimental data seems to suggest different material properties in the aponeurotic and free tendon regions [39]. Contrary to this, however, Scott and Loeb reported, using a cat model, that collagen organization in the aponeurosis and tendon was similar [45]. Determination of region-specific material parameters, including collagen fiber dispersion, to be used in FE simulations of the AT, may be the focus of future research.

Previous studies have evaluated the importance of time-dependent properties in biomechanical simulations involving ligaments and tendons [31, 42]. The choice of the material model used herein was based on its ability to model the effect of fiber dispersion on a tissue's mechanical behavior [19], which is related to one of this study's hypothesis. The absence of time-dependent properties in the material model can be considered a limitation of the FE model presented in this study. Future studies aimed at developing a material model that features both fiber dispersion and time-dependent properties are of interest.

Due to the limited range of the MRI imaging coil, the distal gastrocnemius MTJ could not be visualized and, consequently, could not be included in the model. Because of this, direct comparisons with the literature regarding differential strain patterns of the aponeurotic and free tendon were limited. Nevertheless, an interesting feature of the mechanical behavior of the AT aponeurosis was qualitatively appreciated in the model: widening and flattening during muscular contraction. This behavior has also been previously noted in *in vivo* and *in vitro* studies [5, 24]. Further studies may be directed at improving the understanding of how strain patterns along the whole AT might influence tendon injury mechanics.

CONCLUSION

The aponeurotic and free Achilles tendon finite element model developed was shown to predict adequately, provided that subtendon sliding was allowed, the in vivo tendon behavior, namely regarding longitudinal strain, changes in cross-sectional area, transverse plane rotation, and sagittal plane nodal displacements. Regarding subtendon interface modeling, limiting transverse displacement may be needed to prevent unexpected soleus subtendon transverse sliding. Model outputs were most sensitive to variations in subtendon twist and dispersion of the collagen fiber orientations.

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CHAPTER 4
Does free tendon length influence the injury risk of the Achilles tendon? A finite element study

Submitted for publication.

INTRODUCTION

The Achilles tendon (AT) is a common site of injury. Disorders of the AT can be divided into spontaneous ruptures and overuse injuries [23]. The latter include mid-portion and insertional tendinopathy, paratendinopathy, and superficial and retrocalcaneal bursitis [13]. Mid-portion tendinopathy is the most common of the overuse injuries [23]. The underlaying cause of this disorder has been suggested to be the result of an imbalance between "protective/regenerative responses and damaging/degenerative changes", that may be the outcome of chronic tendon overloading or metabolic diseases [2]. When those changes are extensive enough or large loads are involved, rupture may occur [11]. Accordingly, degenerative changes are expected in histological examinations of patients with AT ruptures [27, 37, 56].

Prevalence of mid-portion AT tendinopathy in the general adult population is 0.24% [24], but it can be significantly higher in active populations, such as recreative runners, to where it has been reported to be 5.2% in a cohort of 1929 subjects [32]. Studies, evaluating the occurrence of AT rupture in patients with previously diagnosed mid-portion tendinopathy, have reported a prevalence of 4.0 to 14.6% [36, 38, 59], with the incidence of AT ruptures in the general population being reported to be 11.2 to 30.87 per 100,000 person-years and seems to be increasing [18, 33, 40, 46], possibly owing to increased participation of older adults in sports [34].

The etiology of tendinopathy is multifactorial [23, 51], with extrinsic and intrinsic factors being implicated. Extrinsic factors include general factors, such as the use of fluoroquinolones or corticosteroids [30], and sports-related factors, which include overtraining and environmental conditions (e.g., hot or cold weather) [22, 26]. Intrinsic factors include systemic factors, such as gender, age, and metabolic disorders (e.g., obesity, hypercholesterolemia) [1, 51], and local factors, such as lower limb biomechanics [6] and AT structural anatomy [51].

The influence of AT geometry in its mechanical behavior has been the focus of previous finite element (FE) studies. A study by Hansen et al. [21] has shown that stress distribution in the free tendon is more sensitive to subject-specific geometry than material properties, with similar findings reported in other studies [47, 49, 60].

Another study by Shim et al. [48], aimed at assessing how subtendon twist affected stress distribution and rupture load in the AT, reported that a twist angle of 30 degrees led to an improvement in AT strength of up to 40%. From these studies, it can be garnered that some aspects of the AT geometry may influence injury risk profiles. However, an important limitation of these studies is that they were focused only on the free tendon, whereas recent research has shown possible involvement of the aponeurotic AT in tendinopathy and rupture cases [43]. Despite its clinical relevance, an improved understanding of how specific geometrical features may impact the mechanical behavior of the AT and its risk of injury is still missing from current literature.

The objective of this study was to evaluate how changes in free tendon length influence the injury risk of the AT using a previously validated 3D FE model of the aponeurotic and free AT. It was hypothesized that an increased free tendon length could be a risk factor for AT injury.

MATERIALS AND METHODS

For the development of AT models with different free tendon lengths, this study uses as basis a previously validated FE model of the AT [15], which is briefly described in the following sections. For a more in depth description of this model and its validation, the interested reader is referred to [15].

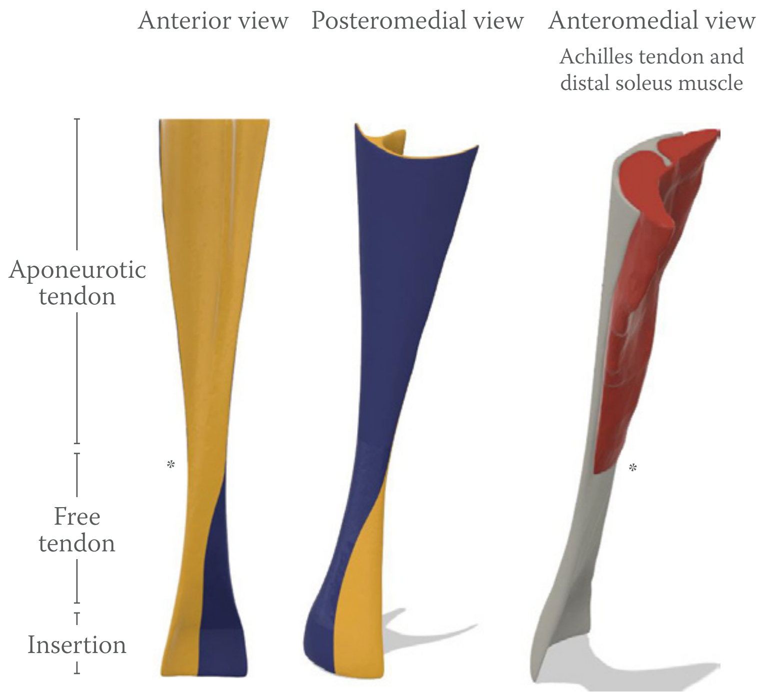
Finite element models

Geometrical models

A 3D model of the free and aponeurotic AT was created, using a previously described software pipeline [45], from magnetic resonance imaging scans of a 34-year-old male (height: 180 cm; mass: 77 Kg), healthy and recreationally active, with no previous injury to the AT. An ultrasound scan was performed in order to estimate the total soleus muscle volume based on the formula described by Bandholm et al. [5].

In this model, hereafter referenced as the "baseline model", a moderate degree of twisting was implemented, as described by Edama et al. [16], between the gastrocnemius and soleus subtendons. The distal soleus muscle was also added to the model to estimate its muscle volume and fiber directions (Figure 19).

FIGURE 19 | General overview of the baseline model. *: myotendinous junction.



The baseline model was then imported into Blender [10], where a free-form deformation (FFD) algorithm was used to create geometrical variation models, as performed in previous FE studies [21, 47–49]. A lattice with 12 vertices distributed across three levels was created, centered on the distal myotendinous junction (MTJ) of the soleus muscle, and aligned with the model's longitudinal and transversal axes. The four midway points were moved in the longitudinal direction, at a distance corresponding to 25% of the free tendon length, to generate free tendon length variation models, while minimizing changes to other geometric features. Two AT models, with 25% larger and smaller free tendon lengths with respect to the baseline model, were generated.

The resulting AT and soleus muscle models were imported into Abaqus 6.14 (Dassault Systèmes, Waltham, MA, USA) for the generation of 3D FE models. The AT and soleus muscle structures were meshed using hybrid quadratic tetrahedral elements (C3D10H).

Material model

The AT was represented as a transversely isotropic hyperelastic material. This study uses the constitutive model proposed by Gasser et al. (2006) [19], in which the strain energy function $\overline{\Psi}$ for an incompressible material is represented as:

$$\overline{\Psi} = \begin{cases} C_{10}(\bar{I}_1 - 3) & \bar{I}_4 < 1 \\ C_{10}(\bar{I}_1 - 3) + \frac{k_1}{2k_2}\left(e^{k_2(k(\bar{I}_1-3)+(1-3k)(\bar{I}_4-1))^2} - 1\right)' & \bar{I}_4 \geq 1' \end{cases} \quad (1)$$

where C_{10}, k_1, k_2, and k are material parameters, I_1 is the first strain invariant, and I_4 is the fourth strain invariant. Tendon fiber directions were estimated using a heat flux simulation conducted on each subtendon [8]. Excluding the parameter k, the constitutive parameters were obtained by fitting the material model to experimental data [47]. Since no specific data on the AT was found for the parameter k, data on the supraspinatus tendon was used [25]. The material properties used in the FE analyses are summarized in Table 6.

TABLE 6 | MATERIAL PARAMETERS

MATERIAL PARAMETERS	
C_{10}	30.549
D	0
k_1	327.345
k_2	0.01
k [25]	0.139

Material parameters used in the finite element analyses.

Loading, boundary, and interaction conditions

The loading conditions considered simulated an isometric plantarflexion contraction with the ankle in a neutral position. Loads were distributed by the soleus, medial and lateral gastrocnemius in a 62%, 26%, and 12% proportion, respectively [3]. The distal soleus muscle, pulling on the ventral surface of the aponeurotic portion of the AT, was estimated to produce 6.52% of the total soleus muscle load [29]. The AT insertion was fixed in the x, y, and z directions. In addition, the proximal surfaces of the tendon were constrained to move only in the direction of the force loads applied to them.

The subtendons interface was modeled using an anisotropic contact formulation without separation, for which friction coefficients of 1 and 0 were defined for the transverse and longitudinal directions, respectively. Such contact formulation was used to allow subtendon sliding in the longitudinal direction, a feature previously deemed necessary for accurate simulation of subtendon dynamics [20], and provide some degree of restriction against transversal plane sliding, based on the assumption that transverse sliding may be limited *in vivo* by the subtendon interface and the presence of the paratenon and *fascia cruris*.

Injury risk analysis

An *in silico* tendon loading experiment was performed to assess whether changes in free tendon length influence the injury risk profile. The AT in the FE models was sequentially loaded, in 100 N increments, from 2500 N to 3500 N. Assuming ATs tend to rupture when subjected to strains above 10% [58], maximum principal strains in the AT were evaluated to investigate its risk of injury. Using a script developed in MATLAB R2019a (Math Works, Natick, MA, USA), the volume of elements in the model exhibiting a maximal principal strain above 10% was recorded. Elements close to boundary conditions were excluded under Saint-Venant's principle [17]. Like in previous studies [44, 47, 48], an AT rupture was considered to have occurred if a continuous group of elements, with a volume of at least 3 mm^3, exhibited a maximum principal strain above 10%. The smallest load meeting the rupture criterion and the respective rupture location were noted for each model.

Sensitivity analyses on subtendon division and interaction

Sensitivity analyses were conducted to assess the influence of geometrical variations in subtendon division and of subtendon interaction in the experiment results.

To create these additional variations, a lattice with eight vertices distributed across two levels was created in Blender, with the upper limit on the distal soleus MTJ, and aligned with the models' longitudinal and transversal axes. The four lower points were rotated in the same plane about a pivot point calculated from the centroid of these four points. Each point was rotated ± 22.5 degrees, effectively creating two additional models of subtendon division comprising small variations in subtendon twisting (Figure 20) for the *short*, baseline, and *long* free tendon models.

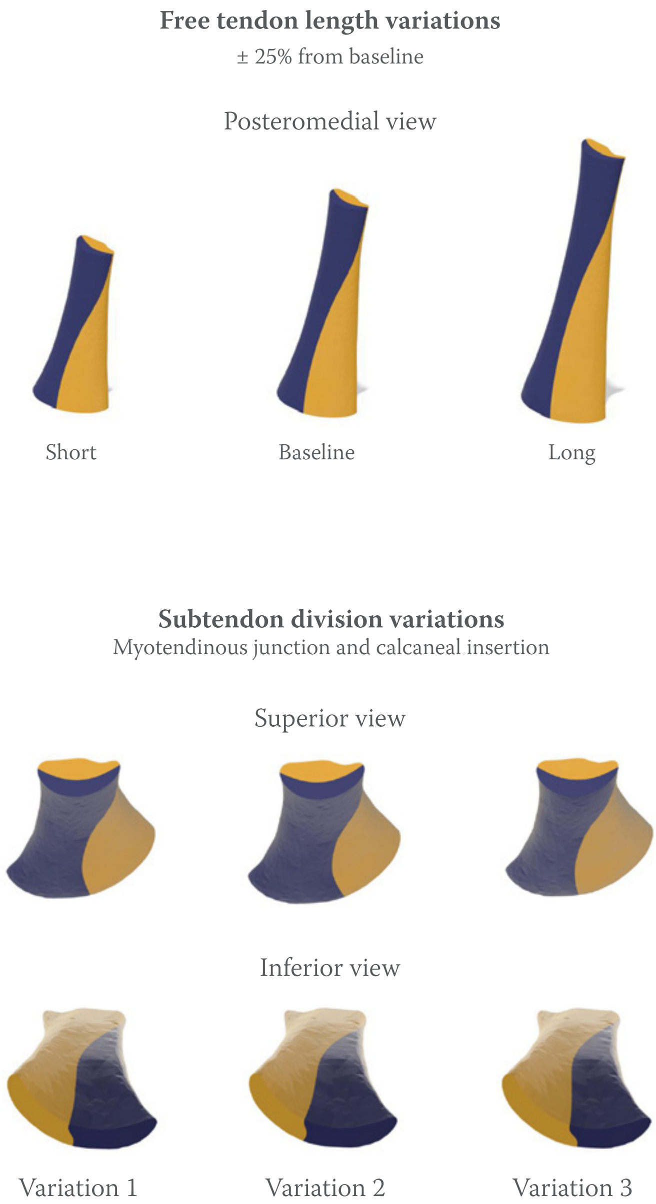


FIGURE 20 | Models included in the study with length and subtendon twist variations.

Because the FFD method used throughout this study could have unintentionally introduced changes in the cross-sectional area (CSA) near the MTJ, this feature was evaluated in all models by conducting additional analyses. Differences in CSA were adjusted using FFD in the *short* and *long* models, similarly to what was described for variations in free tendon length. Briefly, the square made from selecting the four lattice points at the MTJ was scaled up or down to match the CSA in the baseline model at the MTJ. General geometric features of the AT in the free tendon length and subtendon division variation models can be found in Table 7.

TABLE 7 | GEOMETRIC FEATURES OF THE MODELS

MODEL	ST DIVISION	FT LENGTH (MM)	VOLUME (MM^3)	CSA AT MTJ (MM^2)	CSA AT INSERTION (MM^2)	
					SOLEUS ST	GASTROCNEMIUS ST
SHORT	Variation 1	46.6	12527	57.3	44.57	42.09
	Variation 2				40.89	45.77
	Variation 3				48.92	37.75
BASELINE	Variation 1	61.9	12564	57.6	39.06	38.62
	Variation 2				35.52	42.24
	Variation 3				42.92	34.80
LONG	Variation 1	77.1	12562	58.8	35.87	37.02
	Variation 2				32.43	37.02
	Variation 3				39.75	33.14

Geometric features of the models. CSA: cross-sectional area. FT: Free tendon. MTJ: myotendinous junction. ST: subtendon.

Finally, the baseline model loading experiment was repeated with a no-sliding contact condition, i.e., considering the subtendons bonded, to assess the influence of decreased subtendon sliding.

Statistical analysis

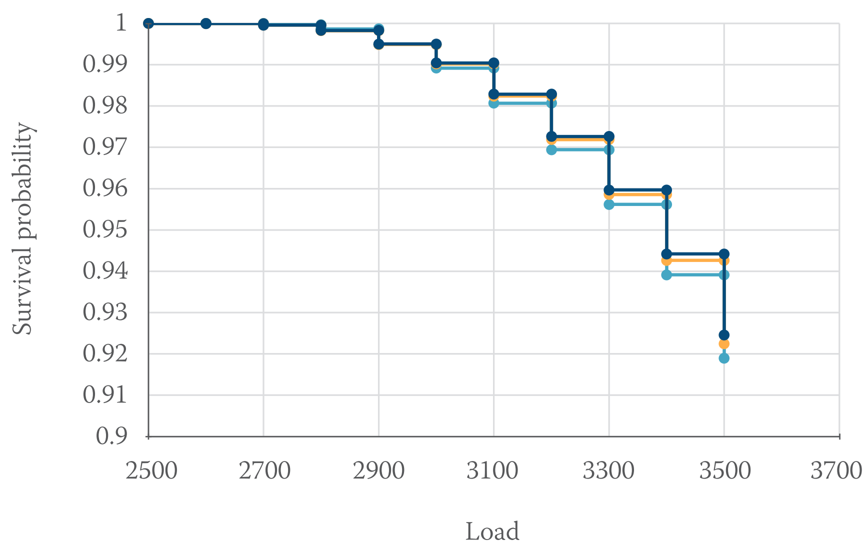
Statistical analyses were performed using Microsoft Excel for Mac V16.45 (Microsoft Corporation, Redmond, WA, USA). Descriptive statistics are represented as means and standard deviations, except where otherwise specified. Kaplan-Meier survival analysis was conducted using the volume of elements showing maximum principal strains above 10%. Survival curves were compared using the log-rank test. The Pearson's correlation coefficient was used to explore potential correlations between variables. Statistical significance was set at $p < 0.01$.

RESULTS

Injury risk analysis

Kaplan-Meier survival plots, related to model elements that result on maximum principal strains above 10%, are shown in Figure 21 for the developed FE models. The log-rank test did not find statistically significant differences across models (Table 8). Rupture loads were similar for *short*, baseline and *long* free tendon models (Table 9).

VARIATION 1



VARIATION 2

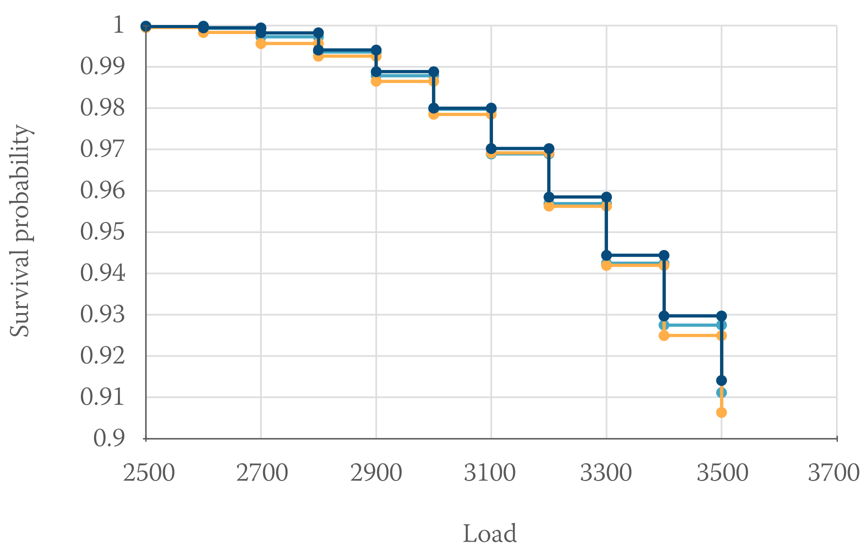
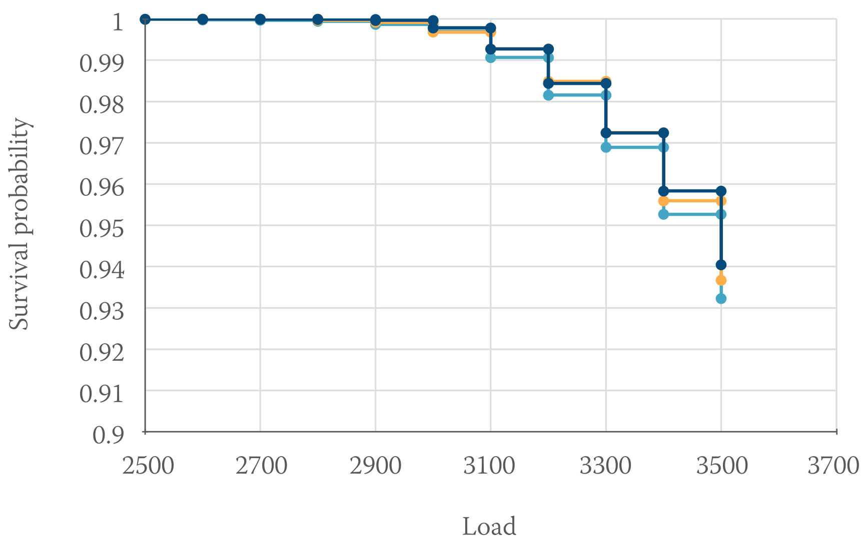


FIGURE 21 | Kaplan-Meier survival analysis. The model was sequentially loaded in 100 N increments, starting with 2500 N to 3500 N. Elements exhibiting a maximum principal strain above 10% are considered damaged. N: Newtons.

Baseline
Short
Long

VARIATION 3



VARIATION 1 / NO SLIDING

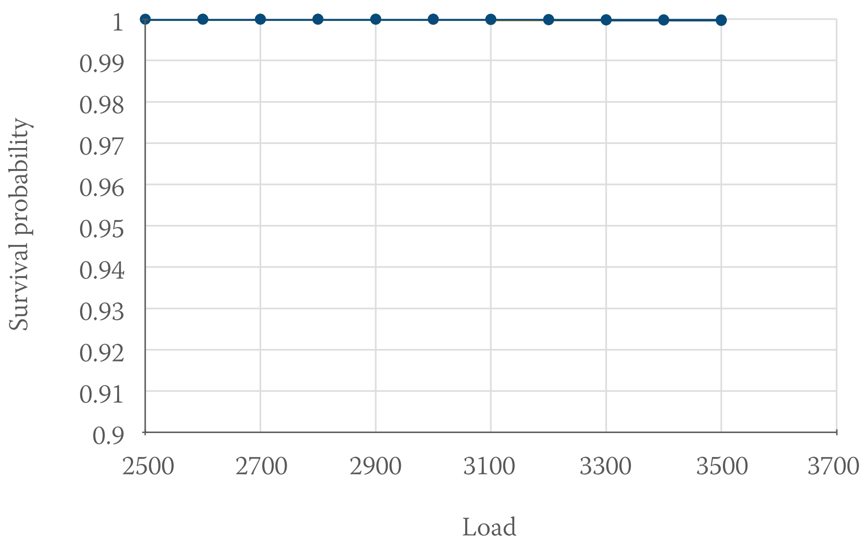


TABLE 8 | P-VALUES OF LOG-RANK TEST COMPARING SURVIVAL CURVES

P-values of log-rank test comparing survival curves in the different model variations. No sliding: Variation 1 model with no sliding contact condition. Statistical significance was set at $p < 0.01$.

	BASELINE *VERSUS* SHORT	BASELINE *VERSUS* LONG	SHORT *VERSUS* LONG
Variation 1	0.325	0.134	0.310
Variation 2	0.250	0.458	0.058
Variation 3	0.201	0.017	0.275
No sliding	0.587	0.629	0.948

TABLE 9 | RUPTURE LOADS IN THE DIFFERENT MODELS.

	SHORT	BASELINE	LONG
Variation 1	2700 (2700)	2800	2800
Variation 2	2500 (2600)	2600	2600
Variation 3	2900	2900	3000 (2900)

Rupture loads in the different models. Loads are expressed in Newtons (N). Values between parenthesis correspond to rupture loads after correction of differences in cross-sectional area at the myotendinous junction between models with the same subtendon division variation.

The rupture location was near the MTJ (Figure 22) on the medial side for all the models. This location coincided with the lowest CSA of the AT. The soleus subtendon exhibited the largest volume of elements exceeding a maximum principal strain of 10%.

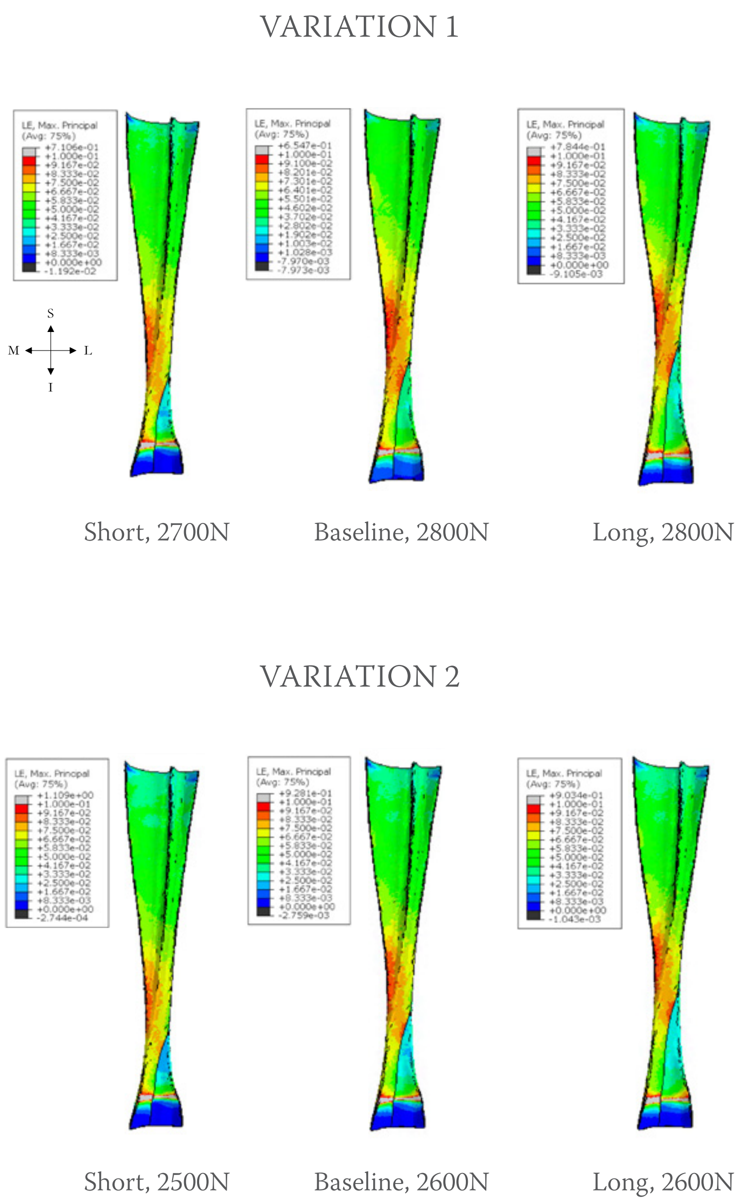
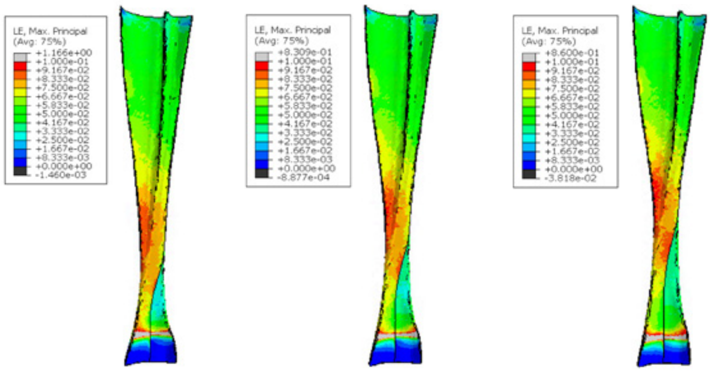


FIGURE 22 | Strain distribution in the FE models at rupture load. Rupture was considered to have occurred if a continuous group of elements with a volume of at least 3 mm^3 exhibited a maximum principal strain above 10%. N: Newtons. I: inferior. L: lateral. M: medial: S: superior.

VARIATION 3



Short, 2900N Baseline, 2900N Long, 3000N

Sensitivity analyses

Variations in subtendon division led to noticeable differences in rupture load. The percentage of the AT CSAs pertaining to the soleus and to the gastrocnemius subtendons were directly (r = 0.87, 99% confidence interval (CI) [0.27, 0.98]) and inversely (r = -0.94, 99% CI [-0.99, -0.6]) correlated with the rupture load, respectively.

The small differences in the rupture load among models, within the same subtendon division, were not found after correction of differences in CSA at the MTJ (Table 9).

When the tendon loading experiment simulations were run with a no-sliding condition, none of the AT models met the defined rupture criterion within the 2500 to 3500 N loading range. Furthermore, the number of elements evidencing maximum principal strains above 10% was low (Figure 21).

DISCUSSION

This study's objective was to evaluate whether variations in free tendon length influence the AT's risk of injury. Using a previously validated FE model and FFD to create additional anatomical models, we did not find evidence of the influence of the free tendon length on the risk of AT injury.

While comparing the MRIs of 72 patients with clinically suspected and MRI confirmed Achilles tendinopathy with the MRIs of 72 control subjects, Szaro et al. [16] found that the free AT length was significantly longer in the tendinopathy group than in the control group (59.7 mm versus 38.5 mm, respectively). Conversely, other studies found no relationship between free AT length and sports activity [31] or tendinopathy [39]. The results of the present study suggest that AT length variations have little influence on the injury risk, supporting the latter studies. However, it could be argued that increased free AT length may instead be a consequence of tendinopathy. Tendinopathic tendons exhibit inferior material properties [42], which have been correlated with a compensatory increase in AT CSA [12, 49]. Coincidentally, in another study, Szaro et al. found that AT length and thickness measured in MRI were positively correlated [55].

In the present study, variations in subtendon CSA were found to influence the risk of AT injury: rupture loads were correlated with subtendon CSAs. Previous studies have noted the significant sensitivity of AT FE models to tendon CSA [48, 49], but the interplay between soleus and gastrocnemius subtendons' CSAs is a previously unreported finding. Effectively, a reduction of the soleus subtendon CSA led to a decrease in the load needed to rupture in the simulated rupture experiment, which is related to the soleus muscle being responsible for 62% of the triceps surae load in the present model [3]. Note that if most of the load had been considered to be exerted by the gastrocnemius muscles, the opposite effect would have been found.

The location of AT ruptures in the tendon midportion has been hypothesized to be related to impaired regional vascularization [7]. However, this notion of blood flow impairment in the AT midportion has been challenged by Astroöm et al. [4]. These authors used laser Doppler flow analysis to evaluate blood flow in the tendon in real-time in 28 healthy volunteers and found that blood flow was evenly distributed throughout the tendon with a slight decrease at the calcaneal insertion. In the present study, the highest AT strains were located in the section with the smallest CSA, suggesting that factors other than vascularization, such as a smaller CSA, may be related to degenerative changes and rupture in the midportion.

When running the simulations with a no-sliding condition between subtendons, the volume of total elements experiencing strains above 10% was significantly reduced. Moreover, none of the models failed in the simulated rupture experiment. One possible explanation for this finding is that by tying the subtendons, the cross-sectional area available for force transmission is considerably increased. Interestingly, experimental studies involving older subjects, both humans [17, 52] and equines [57], have reported decreased subtendon sliding, leading their authors to hypothesize that this decreased differential displacement could be a risk factor for tendinopathy [50], as this disorder is more common in older subjects. However, from this study's perspective, it could also be argued that decreased subtendon sliding may be a protective adaptation in degenerated tendons.

Clinical significance

This study's results show that a decreased subtendon CSA may be a risk factor for rupture, most notably when the corresponding triceps surae muscle is the dominant force in ankle plantarflexion. Accordingly, triceps surae muscles' activation dynamics may lead to non-uniform displacement patterns in the AT, as demonstrated in an *in vivo* experiment by Clark and Franz [9]. In addition, a previously reported investigation, using biplanar ultrasound imaging, has suggested that the largest displacements in the AT are located in tissue most likely belonging to the soleus subtendon [52].

The typical injury mechanism of ATs involves a forced ankle plantarflexion contraction with the knee in extension or early flexion [35]. Interestingly, concurrent activation of knee extensor muscles during plantarflexion leads to selective activation of the soleus muscle and decreased activity of the gastrocnemius muscle [53]. In addition, decreased activation of the gastrocnemius muscles has also been noted in older individuals [28]. Of note, the percentage of contribution of the soleus subtendon to the total Achilles volume ranges from 34 to 52% [41]. Thus, it can be hypothesized that decreased concurrent activation of the gastrocnemius and soleus muscles during the push-off movement can put the tendon at risk of rupture by over-soliciting the soleus subtendon in susceptible individuals, i.e., those with a soleus subtendon CSA on the lower end range.

The ability to identify AT subtendons' distribution is currently limited [54], but as imaging methods improve it may become a reality. Regardless, the implementation of exercises to improve co-contraction of gastrocnemius and soleus muscles during push-off or changes of direction may be a valuable prevention strategy in susceptible-to-injury groups, e.g., older athletes in sports such as basketball and soccer [14, 35], and those with previous AT tendinopathy [59].

Limitations

This study's main limitation is the possibility of unwittingly adding unwarranted features or anatomic variations to the baseline FE model, while performing FFD to model variations in free tendon length or tendinopathy. To account for this possibility, all AT models were carefully inspected, and if these unexpected concurrent variations were found, appropriate sensitivity analyses were conducted to assess their possible influence on the results obtained. This study is also based on the AT geometry of a single subject. Therefore, it could be argued that specific AT geometries and subtendon divisions may be more susceptible to AT ruptures. Two additional subtendon twist variation models were created to account for this possibility, but despite this, other geometrical features related to the overall shape of the tendon could influence the study's results.

Future research

Assessing the specific contribution of each subtendon to the total AT volume may be helpful to detect susceptibility to injury for conditions of increased differential displacement of the subtendons. Thus, methods to assess fiber direction, dispersion, or subtendon division may be of interest for biomechanical investigations and possibly to the development of injury susceptibility models. Future FE studies may evaluate the gastrocnemius-soleus subtendon dynamics, particularly in modeling the subtendon interface when simulating specific patients' situations or performing given tasks.

CONCLUSION

Free AT length had no influence on tendon strain and rupture load, provided other parameters and features were kept constant. Rupture load was sensitive to changes in subtendon CSA size. Increased force transmission between subtendons, due to a decreased subtendon sliding condition, caused fewer elements to experience strains above the failure criterion.

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CHAPTER 5

Progression of partial to complete ruptures of the Achilles tendon during rehabilitation: a study using a finite element model

Submitted for publication

INTRODUCTION

Injuries to the Achilles tendon (AT) are common. Specifically, complete ruptures of the AT have an incidence of 10.8 to 30.2 per 100,000 person-years [5]. Although considerable research has been devoted to complete Achilles tendon ruptures (ATRs), information on how to diagnose and manage partial ruptures is comparatively sparse. Effectively, no clear guidelines exist for the treatment of partial ATRs, with both conservative and surgical interventions being proposed [14]. Although conservative management is commonly considered acceptable in partial tendon ruptures affecting less than 50% of the tendon's width [14], supporting experimental evidence for this "50% rule" is currently lacking.

The AT is the confluence of the gastrocnemius and soleus subtendons, which twist around each other, clockwise in a left AT and counter-clockwise in a right AT, before inserting in the calcaneal tuberosity on the calcaneus [12]. In the literature, varying degrees of subtendon twisting have been reported and are typically categorized into small, moderate, or extreme. Of note, in an AT with a moderate degree of twisting, a partial rupture in the free tendon portion approaching a 50% loss of continuity may imply a near total loss of force transmission in the gastrocnemius or soleus subtendon, depending on whether the rupture is lateral or medial sided, as that subtendon may be almost completely ruptured. Considering the significant reduction in cross-sectional area (CSA) available for force transmission and that a previous study using finite element analysis (FEA) has shown considerable sensitivity to variations in CSA in a simulated rupture experiment [28], such an event could set the conditions for progression to a complete rupture.

Even though conservative and surgical treatments seem to provide similar clinical results in complete ATRs, incidence of re-ruptures is increased almost 10-fold in patients treated conservatively [20]. Of note, patients with re-ruptures have long-term deficits compared to patients without this complication [30]. Accordingly, some physicians advocate for surgical treatment of complete ATRs in an effort to lessen the risk of re-rupture and the associated persistent impairments.

Thus, the objective of this study was to assess the possibility of rupture progression under loading conditions simulating an early functional rehabilitation protocol in partial ATRs of varying severity, using a previously validated finite element (FE) model of the aponeurotic and free AT [11].

MATERIALS AND METHODS

The creation of the FE models used in this study is summarized in the next sections. For an extended description of the design and validation of these models, readers are referred to the study of Diniz et al. [11].

Finite element models

Geometrical models

Using a previously described software pipeline [24], magnetic resonance imaging scans of an healthy and recreationally active 34-year-old male (height: 180 cm; mass: 77 Kg) were used to create a 3D model of the free and aponeurotic AT, and soleus muscle (Figure 23). Three models representing the degrees of twisting reported by Edama et al. [12] – Type 1 (*Least)*, Type 2 (*Moderate)*, and Type 3 (*Extreme)* – were developed (Figure 24).

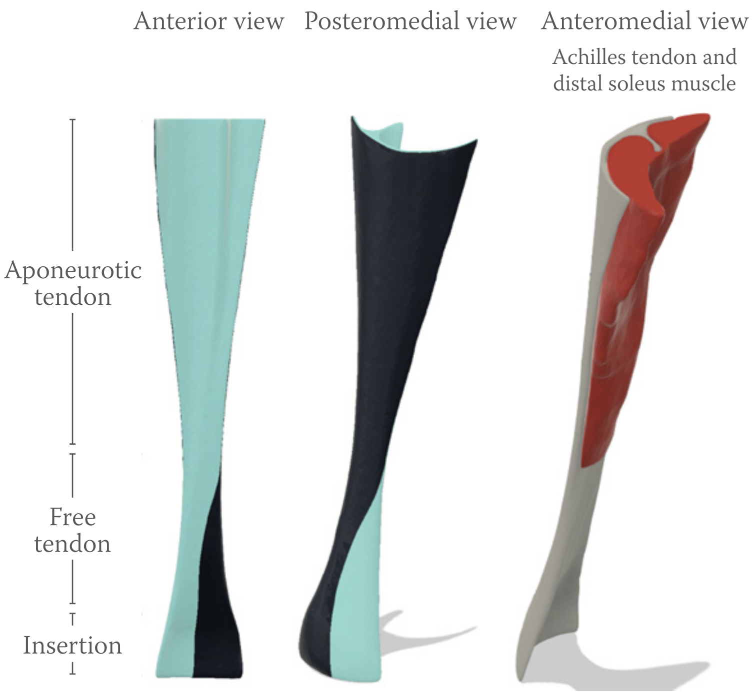


FIGURE 23 | Model geometry.

FIGURE 24 | Different models of subtendon twist, according to the descriptions of Edama et al, used in the finite element analyses [12]. Type 1 corresponds to least twisting (found in 50% of specimens), Type 2 to moderate twisting (found in 43% of specimens), and Type 3 to extreme twisting (found in 7% of specimens). The model corresponds to a left Achilles tendon.

The generated AT and soleus muscle models were imported into Abaqus 6.14 (Dassault Systèmes, Waltham, MA, USA) for the development of 3D FE models using hybrid quadratic tetrahedral elements (C3D10H).

Material model

The constitutive model proposed by Gasser et al. [13] is used in this study, with the AT being considered a transversely isotropic hyperelastic material. Constitutive parameters, with exception of the parameter representing fiber distribution (parameter *k*), were determined by fitting the material model to experimental data from a study by Shim et al. [23, 29]. Average material parameters presented by Shim et al. [29] for healthy and tendinopathic tendons were used in the FE analyses of the present study. For the parameter *k*, data from the supraspinatus tendon [17] was used since no specific data on the AT could be found. A heat flux stimulation was conducted on each subtendon to estimate the tendon fibers' directions [6].

Loading, boundary conditions, and interactions

The FE models simulated an isometric plantarflexion contraction with the ankle in a neutral position. The soleus, medial and lateral gastrocnemius muscles contributed with 62%, 26%, and 12% of the loads, respectively [3]. The portion of the distal soleus muscle that pulled on the ventral surface of the aponeurotic AT was estimated to contribute with 6.52% of the total soleus muscle load [18]. The AT insertion was considered to be fixed in the x, y, and z directions. Additionally, the movement of the proximal extremities of the soleus and gastrocnemius subtendons was constrained to be only in the direction of the forces applied.

The subtendons' interface was assumed bonded using a *tie* constraint. Such formulation was used to prevent subtendon sliding. Although subtendon sliding is a feature previously deemed necessary for accurate simulation of subtendon dynamics [11, 16], it was avoided in this experiment because certain partial rupture conditions would cause rigid body motion due to the disconnection of both subtendon ends. Nonetheless, a previous FE analysis using the present model showed that the load necessary to cause rupture is considerably increased when subtendon sliding is not allowed, and, thus, the present study provides a *best-case scenario* regarding partial ruptures. An overview of the computational model parameters can be found in Table 10.

TABLE 10 | MODEL PARAMETERS

PARAMETER	VALUES
Ankle MA[26] (mm)	47
TS PF force contribution	83%
LOAD DISTRIBUTION [3] IN TS	
Soleus	62%
Medial Gastrocnemius	26%
Lateral Gastrocnemius	12%
MATERIAL PARAMETERS – HEALTHY	
C10 (MPa)	12.104
D	0
k1 (MPa)	395.421
k2	0.01
K [17]	0.139
MATERIAL PARAMETERS – TENDINOPATHY	
C10 (MPa)	3.657
D	0
k1 (MPa)	165.091
k2	0.01
k^{14}	0.139

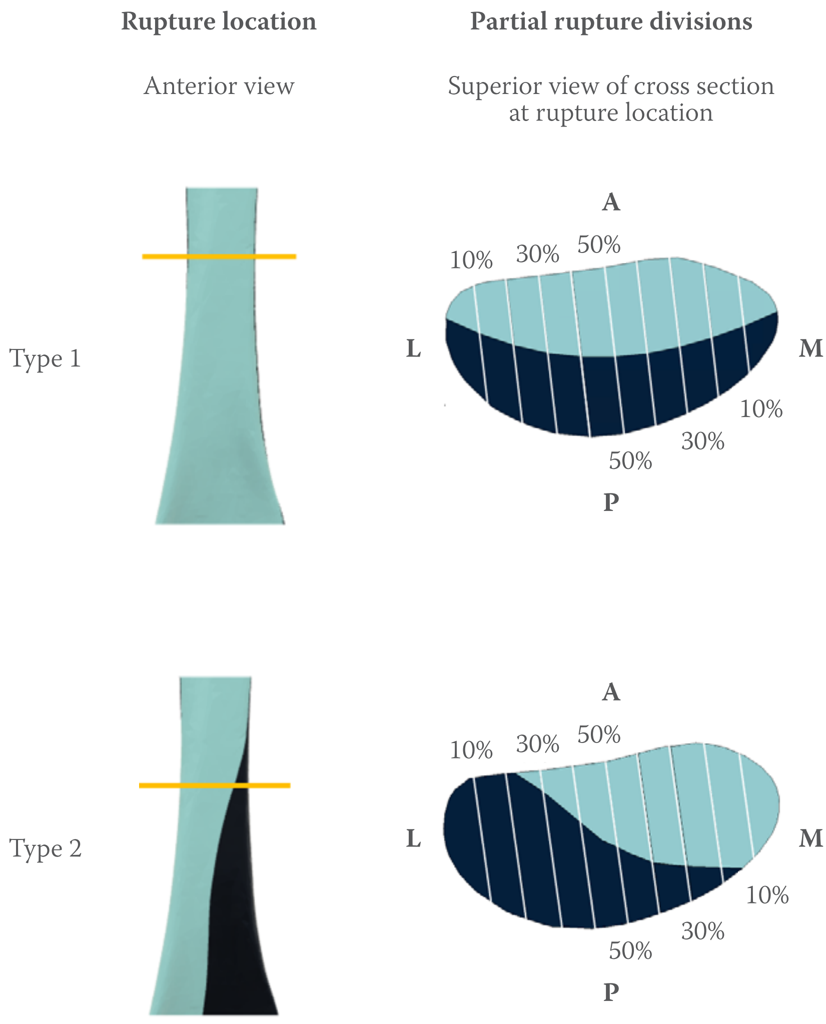
Model parameters used in the finite element analyses.
MA: moment arm.
PF: plantarflexion.
TS: triceps surae.

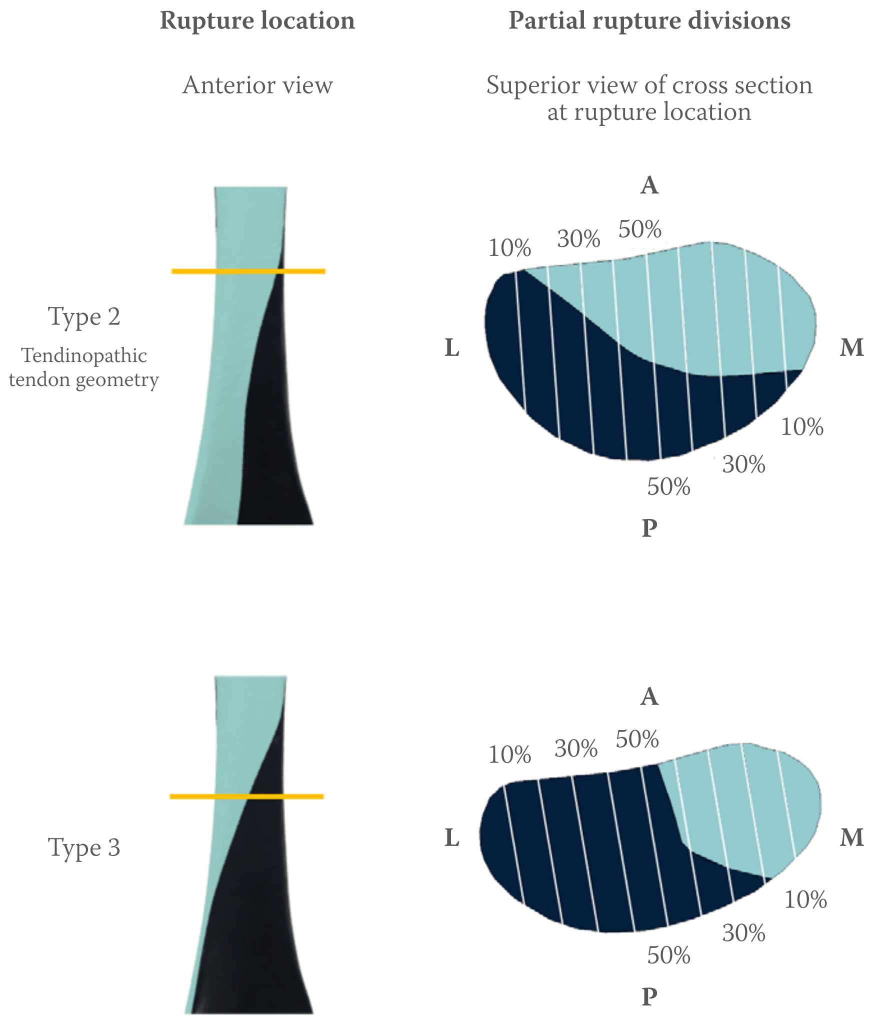
Partial rupture simulation

First, *in silico* tendon rupture experiments were performed using the three FE models with different twisting degrees to identify the most likely tendon rupture sites. Similar simulated rupture experiments can be found in the literature [23, 27, 28]. Starting with 2500 N, FE models were sequentially loaded in 100 N increments until a contiguous group of elements, with a volume of at least 3 mm^3, exhibited a maximum principal strain above 10%. This failure strain value was chosen based on experimental data [31]. The baseline models were then split along a plane perpendicular to the longitudinal tendon axis at the corresponding rupture site and imported to the FEA software.

Partial ruptures were simulated by partitioning the interface between the two halves of the subtendons into 10 sections of 10% of the AT width, along the mediolateral axis. The non-ruptured sections were joined using a tie constraint, while the ruptured sections were left unconstrained, which effectively created partial ruptures in 10% increments. These were created from 10% to 50% starting from the medial and lateral sides (Figure 25).

FIGURE 25 | Rupture locations and partial rupture divisions for different subtendon twist and for the tendinopathic tendon model. Yellow line depicts rupture site. A: anterior. M: medial. L: lateral. P: posterior.





Because the two halves of each subtendon were imported as separate parts, the heat flux simulation used to define fiber directions was ran independently on each part. This caused fiber directions at the rupture site to be different than those in the baseline models. To avoid this problem, a mapping procedure was employed to copy fiber directions from the baseline models, 2 cm proximal and distal to the rupture plane. This was accomplished by pairing elements in both elements and copying the direction of the closest element in the baseline model to the corresponding partial rupture model.

The FE models of the ATRs were loaded with 100 N, 200 N, and 400 N. These forces were chosen because they approximate the force magnitudes experienced by ruptured tendons during rehabilitation [4, 7, 19]. This loading protocol is intended to mimic the loads exerted during passive ankle dorsiflexion (100 N), walking with a cam walker with (190 N) and without a 2.5 cm heel lift (369 N) [2, 7, 22]. Partial ruptures were considered to have progressed if any contiguous group of elements, with a volume larger than 3 mm^3, exhibited a maximum principal strain above 10%.

Sensitivity analyses

Sensitivity analyses were conducted on the Type 2 (moderate twisting) model to assess the influence of the free tendon morphology (considering a tendinopathic AT geometry with tendinopathy material properties), the use of a contact formulation for the subtendon interface (permitting subtendon sliding), and the maximum principal rupture threshold on the experiment results.

To create the tendinopathic AT geometry model, the baseline model of moderate twisting was imported into Blender [9], where a freeform deformation algorithm was used to create a geometrical variation model pertaining to a tendinopathic tendon. A lattice with 92 vertices distributed across 23 levels was created, centered on the distal myotendinous junction of the soleus muscle, and aligned with the model's longitudinal and transversal axes. The 11 most distal levels of the lattice, corresponding to the free tendon region, were deformed to conform to the anteroposterior dimensions found in a tendinopathic AT [21]. For each of these levels, the distances between the two most anterior and the two most posterior points in the lattice were increased in order to match the relative differences between a tendinopathic tendon and that of the contra-lateral limb in patients with unilateral Achilles tendinopathy [21]. The mediolateral distance was kept unchanged in accordance with the experimental data [21]. In addition, the abovementioned material properties pertaining to tendinopathic tendons were used in this model.

To assess whether changing the subtendon contact formulation from a "tied" (no sliding) condition to a sliding condition would change the study results, an anisotropic friction contact formulation was used. In this analysis, subtendon sliding without friction was allowed in the longitudinal direction, but a coefficient of friction of 1 was applied in the transverse direction. Such contact formulation was employed to model anatomical restraints to transverse sliding [11].

Finally, results were reevaluated using 5-, 7.5-, 12.5-, and 15% maximum principal strain thresholds for rupture progression under the same loading conditions. The main research question of the present study was reexamined, i.e., whether partial ruptures with less than 50% loss of continuity could progress under loading conditions prompted by an early functional rehabilitation.

RESULTS

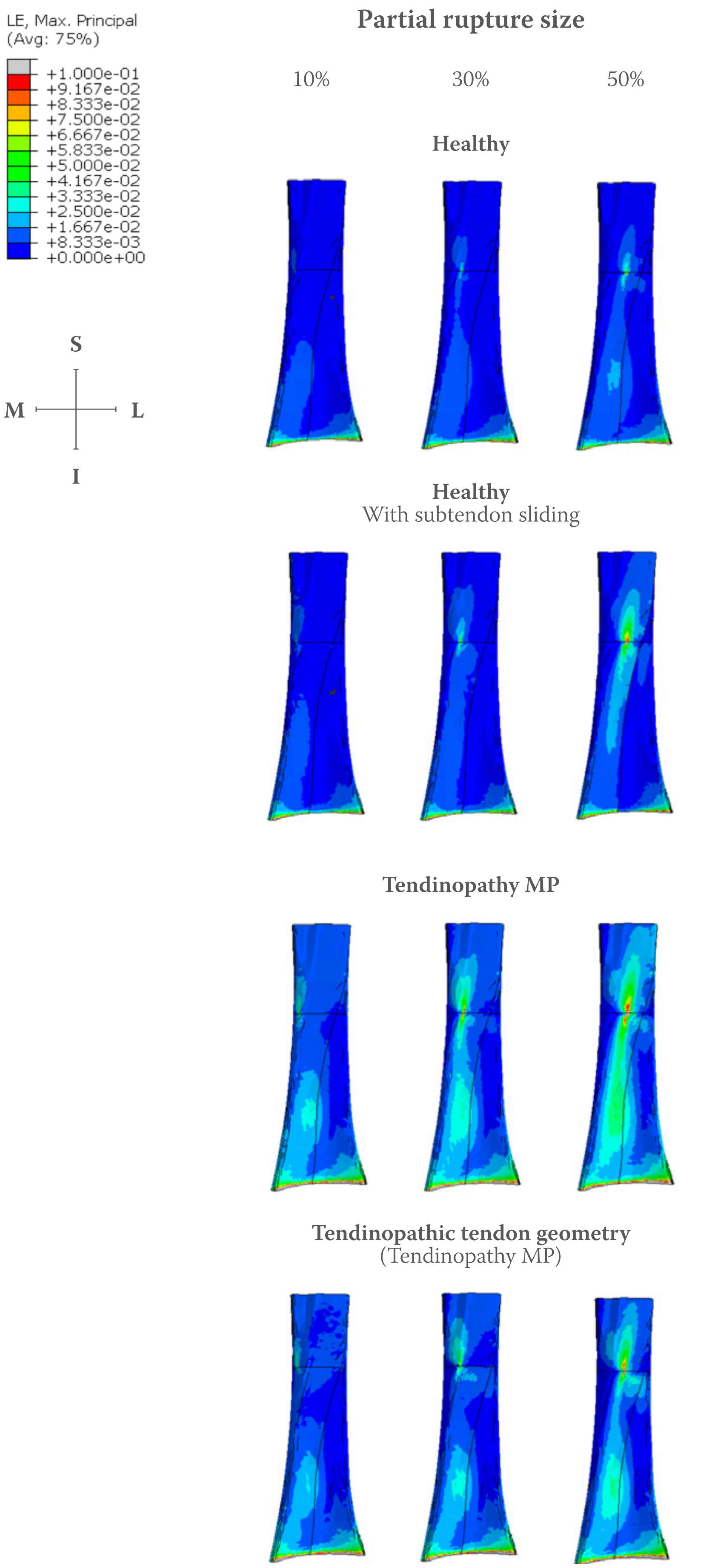
All models showed progression of partial ruptures with less than 50% loss of continuity, regardless of subtendon twisting or material parameters, as detailed in Table 11. As an example, maximum principal strain fields computed for the Type 2 (moderate twisting) tendon under a 200 N load and different modelling conditions are shown in Figure 26.

TABLE 11 | RESULTS OF THE IN SILICO RUPTURE SIMULATION EXPERIMENTS.

		HEALTHY		SLIDING		TENDINOPATHY		TENDINOPATHIC TG	
ST TWIST	R%	M	L	M	L	M	L	M	L
Type 1 *(least)*	10	N/A	N/A			400	400		
	20	400	N/A			200	200		
	30	400	400			100	200		
	40	400	400			100	100		
	50	200	200			100	100		
Type 2 *(moderate)*	10	N/A	N/A	N/A	N/A	200	400	200	400
	20	400	N/A	400	N/A	200	200	200	200
	30	400	400	400	400	100	200	100	200
	40	400	400	200	400	100	100	100	100
	50	200	200	100	200	100	100	100	100
Type 3 *(extreme)*	10	N/A	N/A			200	400		
	20	400	N/A			200	200		
	30	400	400			100	200		
	40	200	400			100	100		
	50	200	200			100	100		

Results of the *in silico* rupture simulation experiments. Loads correspond to the lowest load for which a contiguous group of elements with a volume larger than 3 mm^3 exhibited a maximum principal strain above 10%. Subtendon twists are categorized according to the Edama classification [12]. L: lateral sided rupture. M: medial sided rupture. N/A: not applicable, i.e., the rupture progression criterion was not met. R%: percentage of mediolateral width continuity lost. ST: subtendon. Tendinopathic TG: tendinopathic tendon geometry model. Color scheme relates to approximate loads exerted on the Achilles tendon: green color corresponds to walking without a 2.5 cm heel lift in a cam walker boot (369 N), yellow color to walking with a 2.5 cm heel lift in a cam walker boot (190 N), and orange color to passive ankle dorsiflexion (100 N) [2, 7, 22].

FIGURE 26 | Maximum principal strain field (LE, Max Principal), computed for a 200 N load in the Type 2 (moderate twisting) tendon. Strain fields are represented in the non-deformed geometry. Different modelling conditions are represented: baseline model with healthy and tendinopathy material parameters, baseline with healthy material parameters and subtendon sliding, and tendinopathic tendon geometry model with tendinopathy material parameters. Results are displayed for a 10%, 30% and 50% partial rupture from the medial side. M: medial. MP: material properties. L: lateral.



Type 1 (least twisting) tendon models exhibited the least volume of elements matching the rupture criterion, although this effect became less pronounced as partial rupture size increased (Figure 27). Models with material parameters corresponding to tendinopathic tendons presented an increased volume of ruptured elements, which became increasingly distant from the corresponding healthy models with higher loads.

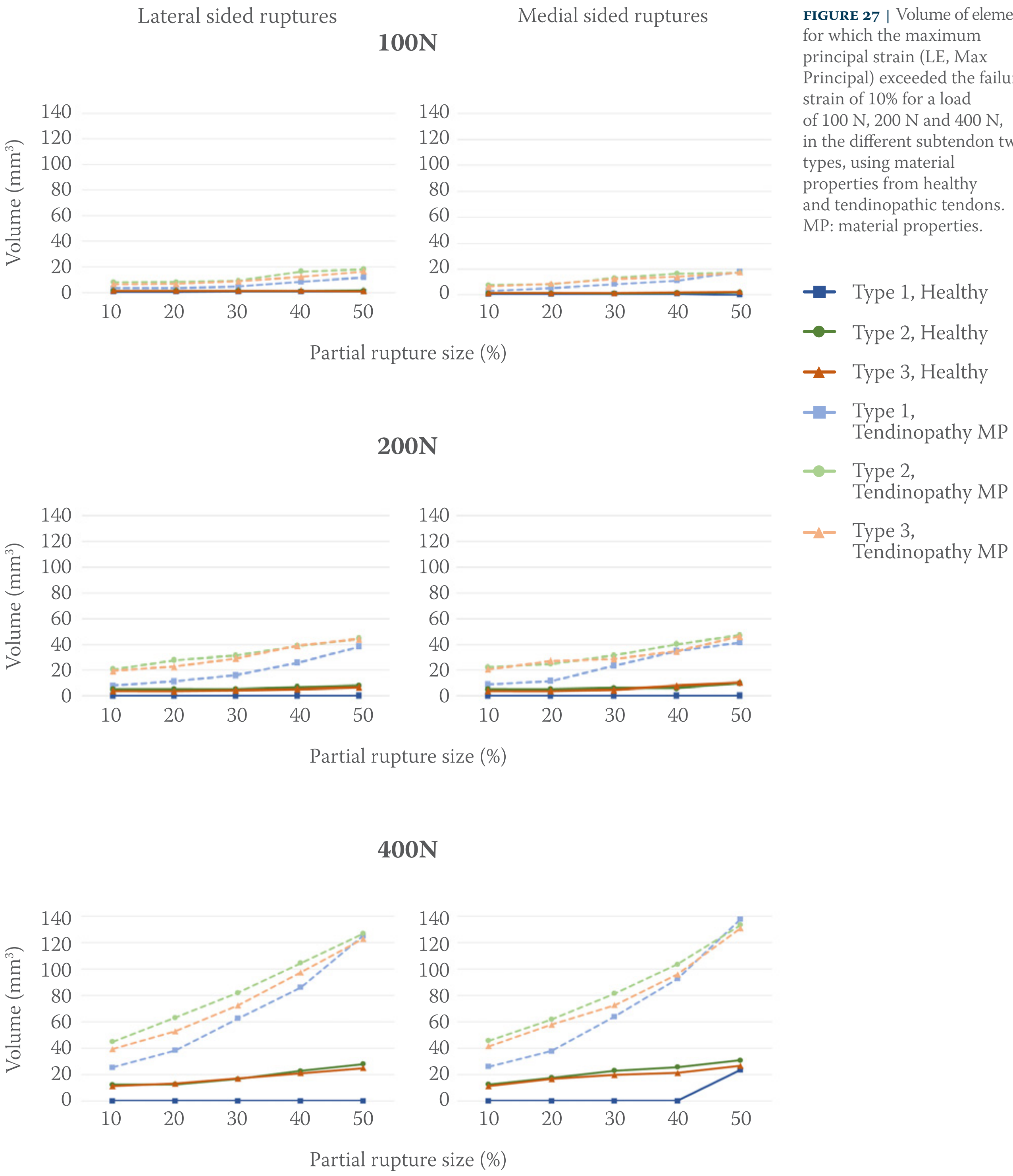
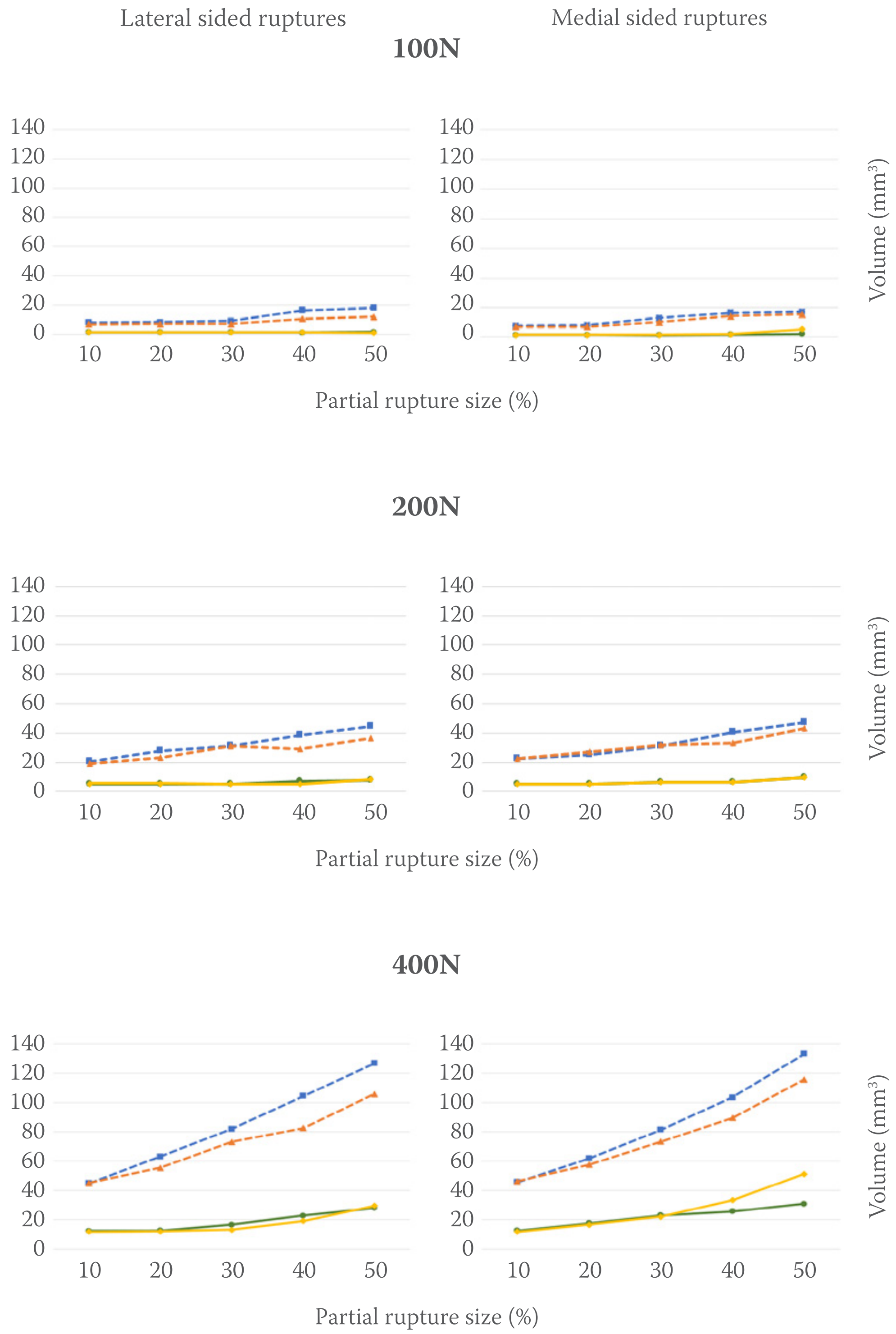


FIGURE 27 | Volume of elements for which the maximum principal strain (LE, Max Principal) exceeded the failure strain of 10% for a load of 100 N, 200 N and 400 N, in the different subtendon twist types, using material properties from healthy and tendinopathic tendons. MP: material properties.

Sensitivity analyses

Additional Type 2 (moderate twisting) models, i.e., considering a tendinopathic tendon geometry and material properties, and a subtendon sliding condition, presented similar results, i.e., partial ruptures progressed even when less than 50% of the free AT width was affected (Figure 28).

FIGURE 28 | Volume of elements for which the maximum principal strain (LE, Max Principal) exceeded the failure strain of 10% for a load of 100 N, 200 N and 400 N, in the different modelling conditions using a Type 2 subtendon twist. The tendinopathic tendon geometry model uses the material properties from tendinopathic tendons. MP: material properties.



Selecting 5-, 7.5-, or 12.5% as maximum principal strain thresholds for the rupture progression criterion did not change this study's main finding, i.e., possible partial rupture progression under early functional rehabilitation, for all subtendon twist configurations and material parameters. Using 15% as maximum principal strain threshold provided a similar outcome only for models with tendinopathic material parameters.

DISCUSSION

The main finding of this study is that loads applied during early functional rehabilitation of partial ruptures exceed model predictions of failure loads for partial ruptures under 50% of the AT mediolateral width.

Current treatment recommendations emphasize functional rehabilitation protocols, regardless of conservative or operative treatment in complete ATRs [10]. As previously stated, there is a paucity of official guidelines for partial ruptures. Considering the findings of this study, physicians advocating surgical treatments of complete ATRs may consider applying the same rationale in partial ruptures, given the likelihood of tear progression with ruptures smaller than 50% of the AT mediolateral width. Furthermore, it may be difficult to establish with precision the real rupture size, or percentage of the tendon affected by the rupture. This may be especially true for ultrasound, given the dependency on the operator. As such, it may be worth considering the possibility of surgical exploration and acute repair for high-demand or active patients. This is especially worth considering given that conservative treatment has an increased risk of re-rupture [20], which entails worse long-term outcomes [30], more so in the high-demand population [15].

In this study, tendon sliding was not allowed, which contrasts with experimental evidence and previous studies stating that to adequately model in vivo behavior tendon sliding is required [11, 16]. However, the aim of the present study was mainly to assess whether the 50% threshold should be used as a cut-off for surgical indication in partial ruptures. Given that previous research has shown that the modelled load necessary to elicit rupture in a computational model is much greater without tendon sliding, the present results can be considered sufficient to conclude that the cut-off for progression to complete rupture is probably less than 50% in real-life conditions. Furthermore, previous *in vivo* research has shown that tendons of older individuals exhibit less subtendon sliding than their younger counterparts [8], and that incidence of AT tendinopathy increases with ageing [1], which further justifies the use of a no-sliding condition.

Previous research has shown that computational models are especially sensitive to variations in CSA [28]. Given that a larger percentage of the force exerted by the triceps surae is transmitted through the soleus subtendon, partial ruptures affecting the medial side may be especially prone to progression, in account of the *endorotation* that the AT suffers as it approaches the calcaneal insertion. A related aspect that should be considered is the several anatomic variations of AT subtendon twisting described in the literature. According to the anatomic descriptions of Edama et al. [12], a 50% medial partial AT rupture will mean that almost all the soleus subtendon has lost continuity in cases of moderate twisting. Furthermore, considering the possibility of subtendon sliding, even a relatively small rupture or transection will translate into a notable increase in strain of that subtendon.

Of note, partial intratendinous or marginal ruptures are sometimes found in chronic tendinopathy patients [14]. In addition, the distinction between partial ruptures and advanced Achilles tendinopathy ruptures may not be so straightforward [25], with the distinction between partial ruptures and focal degenerative changes being particularly difficult [14]. Regardless, partial ruptures and focal degenerative changes imply a loss of ability to transmit load, which in practice signifies a decrease in CSA. Thus, even in the context of chronic tendinopathies, partial tears in the AT should be carefully monitored.

Results of the tendinopathic tendon geometry model were not markedly different from those of the healthy tendon geometry with tendinopathic properties. Despite having an increased CSA, this adaptation, typically present in tendinopathic ATs, was not enough to overcome the decreased material properties. It is interesting to note that previous research has reported that a simulated AT rupture model was more sensitive to changes in geometrical properties than changes in the material parameters [27]. It can be hypothesized that a larger increase in CSA of the tendinopathic tendon model would be able to compensate for the decreased material properties.

This study has four main limitations. First, the model was based on the tendon geometry of a single participant without AT tendinopathy. Possibly, AT tendinopathy is accompanied by geometrical features that were not replicated by the tendon adaptations performed, based on single plane AP and ML dimensions. Second, the tendinopathic model was validated using *in vivo* measurements of healthy tendons. Future studies may be aimed at evaluating the transverse plane rotation, and nodal displacements in the free tendon of patients with AT tendinopathy. Third, this study models partial transections of the tendon, whereas complete ruptures usually show a frayed configuration. However, given that what probably matters is loss of CSA available for force transmission, the present study likely reflects the increased loading of the remaining tendon in such situations. Fourth, loading conditions simulating an uninjured AT were used in this study. It is possible that the pain associated with a partial rupture of the AT leads to inhibition of the muscle corresponding injured subtendon.

Clinical significance

Physicians may use the results of this study to aid in treatment decisions regarding acute partial ruptures of the AT. The current recommendation of treating conservatively ruptures with less than 50% loss may lead to rupture progression when using functional rehabilitation. Given the higher re-rupture risk of conservative treatment [20] and long-lasting decreased outcomes in case of complications [30], treating physicians may want to refer high-demand patients to surgical exploration and repair. Also, given the high model sensitivity to partial ruptures, even smaller grade ruptures need to be carefully monitored.

CONCLUSION

Current protocols of functional rehabilitation of acute partial ruptures of the AT may elicit progression of partial ruptures even with less than 50% loss of continuity. Surgical exploration and repair may be indicated in high-demand patients.

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Section Gamma

Contributing to the improvement of treatment outcomes in Achilles tendon ruptures

CHAPTER 6

Achilles tendon elongation after acute rupture: is it a problem? A systematic review

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INTRODUCTION

Rupture of the Achilles tendon (AT) is a common injury. The incidence of Achilles tendon rupture (ATR) is 18 to 31.17 per 100,000 person-years and is seemingly increasing [17, 32, 61]. These injuries are 3 times more common in men than women, often occurring in recreational athletes aged between 30 and 40 years [25, 36, 37]. Treatment can be operative or non-operative [12, 27, 65]. Unfortunately, strength deficits may persist over the long term [6], possibly owing to elongation of the tendon [46, 48] or resulting inferior mechanical properties [15, 16].

Studies have shown that tendon elongation tends to occur early in the recovery process, with most of tendon lengthening occurring in the first 6 weeks [28, 46, 79]. The AT elongates during a period of up to 6 months after injury, and then undergoes a small shortening from 6 to 12 months [28].

The AT can elongate after acute rupture regardless of operative or non-operative treatment [7, 60]. In patients treated surgically this can be due to gap formation related to knot slipping, suture material creeping deformation, or tissue necrosis [28]. In patients treated non-operatively tendon elongation can be the result of gapping at the time of treatment initiation with subsequent healing in a lengthened position [74].

Several clinical methods of assessing tendon elongation have been described. These include: increased ankle dorsiflexion range of motion (ROM) [10, 39], Matles test [3], Achilles tendon resting angle (ATRA) [8, 78], measurement of the heel-rise height (HRH) [62, 64], and AT tape or ruler measurements [19]. Imaging modalities can also be used to assess tendon lengthening during recovery. This can be performed using metal markers and radiography [46, 48], ultrasound (US) [4, 56, 63] and magnetic resonance imaging (MRI) [30].

The aim of this study was to provide a systematic review of the literature on the prevalence and consequence of tendon elongation in patients after acute ATR treatment. It was hypothesized that an elongated tendon would be associated with a worse clinical outcome.

MATERIALS AND METHODS

This systematic review was conducted according to the PRISMA guidelines [44].

Eligibility criteria

Clinical studies related to ATR with a minimum follow-up of 6 months were eligible for inclusion. Studies were required to report AT length, or provide evidence of tendon elongation, and perform statistical analysis of correlations with clinical or functional outcomes. Also included are biomechanical studies in which AT elongation was a found to be generalized finding in the study group, even if no statistical correlations were investigated. For these studies to be included, the study group had to be compared with a healthy control group, or the injured limb compared with the uninjured limb, regarding biomechanical parameters.

Tendon length could be assessed with either imaging or clinical methods but comparison with the healthy limb was required. Accepted clinical methods included: ATRA, HRH and increased dorsiflexion ankle ROM [3, 39].

The absolute ATRA is defined as the acute angle between the long axis of the fibula and a line from the tip of the fibula to the head of the fifth metatarsal [8]. The relative ATRA corresponds to the difference between the injured an uninjured limbs ATRAs. A negative relative ATRA indicates that the injured limb is in a more dorsiflexed position relative to the uninjured side, thus indicating an elongated AT [78].

HRH is assessed by measuring the distance travelled by the heel in a single leg heel-rise while standing in a 10 degrees inclined platform [62]. The patient is asked to stand on the injured limb in the platform and perform a heel rise. The distance travelled by the heel is noted and the uninjured side is tested next. Differences between limbs are noted. It has been postulated that a deficit in HRH in the injured limb when comparing to the uninjured limb is related to tendon elongation [64].

Systematic reviews were considered as a source of primary studies only. Due to limitations of the research team regarding languages spoken and access to translators, only articles in English, Dutch, French and Spanish were considered eligible for inclusion. The following were considered reasons for exclusion: case reports, narrative review papers and expert opinions, studies related to open or chronic injuries and studies performed on animal models or cadavers.

Information Sources

The databases for MEDLINE, CENTRAL and Web of Science were searched for all published articles. No time restrictions were applied. Relevant references extracted from the articles screened were included for analysis as well. Searches were conducted between April 23rd and 26th of 2019.

Search strategy

The following search string was used: (((Achilles OR calcaneal OR calcaneus OR calcanean) AND (tendon OR tendo)) OR (tendoachilles OR tendocalcaneus)) AND (rupture* OR lesion* OR injur* OR tear*) AND (length OR elongation OR lengthening).

Study selection

From abstract, all studies reporting clinical outcomes of the treatment of acute mid-portion ATR. Language restrictions and other exclusion criteria were applied at the abstract screening stage when possible. The full text of all relevant references was screened for eligibility and other further references of interest.

Selection process and data management

Two reviewers (PD and JP) independently screened and selected studies for full text analysis from title and abstract using the Rayyan QCRI systematic review management app [51]. Disagreement was settled by discussion.

Customized forms, Microsoft Excel and Rayyan QCRI were used for data management. Both reviewers performed data collection and data was extracted in duplicate.

Data items

The following data items were collected: authors, year of publication, journal, evidence level (as graded by The Journal of Bone and Joint Surgery) [40], method of tendon length assessment, type of intervention, number of participants, number of controls (if applicable), sex, age (mean, standard deviation and range, if available), follow-up, tendon length or occurrence of elongation and reference points, statistical correlations or relevant findings related to tendon lengthening or the absence of such findings, and other outcome measures used and their respective values and correlations.

Outcomes and priorization

Primary outcomes were the occurrence of tendon elongation (or tendon length at final follow-up) and its correlation with patient reported outcome measures (PROMs), strength and power evaluations, or biomechanical tests.

Secondary outcomes were any correlation between mean values of tendon elongation and other outcome measures.

Risk of bias in individual studies

The risk of bias in individual studies was assessed using an adapted version of the Quality in Prognosis Studies Tool (QUIPs) [20]. Risk of bias was assessed per study and per outcome (if more than one correlation with tendon length was evaluated). Besides the issues mentioned by the tool itself, some specific issues were also considered.

In the population selection domain, relevant issues included sample size (if sample size estimations were not performed or less than 60 patients were included), duration of follow-up (less than 12 months, or over 10 years with wide ranges and/or aged patients), and whether controls were matched to patients (when applicable).

In the prognostic factor measurement domain, for the measurement of tendon length, studies relying on MRI and US were considered to have the lowest risk of bias, studies using radiographic markers had a moderate risk of bias and the remaining had a high risk.

Regarding the outcome measurement domain, relevant issues to all studies included: if outcomes were assessed at different time points, and if more than one treatment per outcome was reported.

For studies related to PROMs and clinical outcomes, using a non-validated score was considered an issue. For studies evaluating strength and power, using a single joint angle for isometric testing, or not reporting the angle of peak torque or specifying values for different joint angles in isokinetic strength measurements were considered issues. For biomechanical studies, not using motion capture systems, or testing only for low demand tasks (like walking) were significant issues.

In the study confounding domain, the following issues were considered: being a primarily therapeutic study, inadequate descriptions of postoperative rehabilitation and no direct comparisons with healthy controls.

Data synthesis

Data retrieved from studies was pooled into a database and analyzed. Conclusions were formulated according to The Journal of Bone and Joint Surgery Grades of Recommendation [76], as to whether elongation of the AT negatively impacts PROMs, strength and power evaluations and biomechanical parameters.

RESULTS

Search yielded 1063 entries. After removal of duplicate entries, 730 records were screened and 139 were selected for full-text evaluation. Seven of these could not be retrieved. After application of eligibility criteria, 28 papers were selected for inclusion and quality evaluation. Study search and selection flowchart, with exclusion reasons, can be seen in Figure 29.

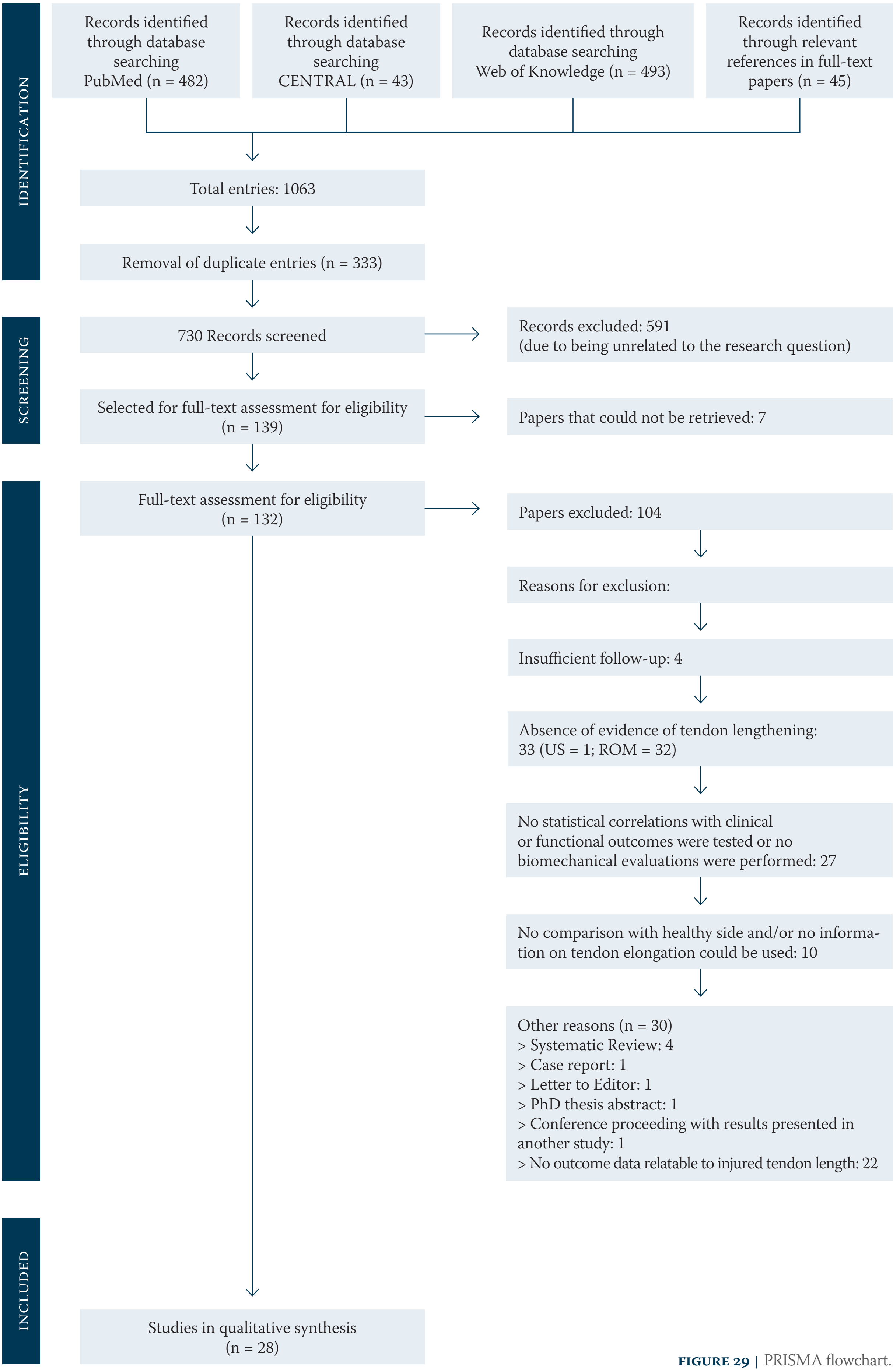

FIGURE 29 | PRISMA flowchart.

General study characteristics

The total number of participants included in this review was 1321, of which 1261 were injured patients and 60 were healthy controls. The number of participants in each study, including controls, ranged from 9 to 125 subjects, and the number of patients ranged from 4 to 125 patients. Average age of included participants in studies ranged from 34.5 years to 49.2 years and ages cumulatively ranged from 20 years and 76 years.

Among all papers there were 17 prognostic studies and 11 therapeutic studies. The prognostic studies [1, 7, 8, 22, 26, 38, 43, 50, 55, 57, 59, 62, 64, 67, 68, 75, 79] evaluated the prognostic factors or consequences of AT ruptures. In the therapeutic intervention studies [9, 13, 21, 24, 28, 41, 45, 52, 58, 60, 71], the study objective was to assess or compare the outcomes of certain treatments, which included measurements related to tendon length and their influence on other outcomes and thus were included in this review.

In the prognostic studies group, nine studies included only surgically treated patients [1, 8, 22, 26, 38, 43, 59, 64, 67], one included only non-operatively treated patients [68] and seven studies included patients treated operatively or non-operatively [7, 50, 55, 57, 62, 75, 79]. In the therapeutic studies group, seven studies included patients treated operatively [9, 21, 28, 45, 52, 58, 71], three studies included patients treated non-operatively [13, 24, 41] and one study included patients treated either operatively or non-operatively [60].

Of the prognostic studies, two were evidence level I [8, 59], five were level II [22, 50, 62, 75, 79], four were level III [7, 26, 57, 68] and six were level IV [1, 38, 43, 55, 64, 67], according to the JBJS Levels of evidence for prognostic studies [77]. In the therapeutic studies group, five were level I [21, 45, 52, 58, 60], one was level II [52], three were level III [9, 41, 71] and two were level IV [13, 24].

Average and minimum follow-up ranged between 6 months and 14 years, and 6 months and 13 years, respectively. Data related to individual study characteristics and patient demographics can be found in Table 12**.**

TABLE 12 | GENERAL STUDY CHARACTERISTICS

AUTHORS	YEAR	LEVEL OF EVIDENCE	STUDY TYPE	TREATMENT
		MRI		
Heikkinen et al. [22]	2017	II	Prognostic	Surgical
Rosso et al. [57]	2013	III	Prognostic	Surgical versus non-operative
		US		
Manegold et al. [38]	2018	IV	Prognostic	Surgical
Powell et al. [55]	2018	IV	Prognostic	Surgical versus non-operative
Zellers et al. [79]	2018	II	Prognostic	Surgical versus non-operative
Brorsson et al. [7]	2017	III	Prognostic	Surgical versus non-operative
Jandacka et al. [26]	2017	III	Prognostic	Surgical
Agres et al. [1]	2015	IV	Prognostic	Surgical
Suydam et al. [67]	2015	IV	Prognostic	Surgical
Silbernagel et al. [64]	2012	IV	Prognostic	Surgical
		RADIOGRAPHY		
Heikkinen et al. [21]	2016	I	Therapeutic	Surgical
Schepull et al. [58]	2013	I	Therapeutic	Surgical
Schepull et al. [60]	2012	I	Therapeutic	Surgical versus non-operative
Pajala et al. [52]	2009	I	Therapeutic	Surgical
Kangas et al. [28]	2007	II	Therapeutic	Surgical
Schepull et al. [59]	2007	I	Prognostic	Surgical
Mortensen et al. [45]	1999	I	Therapeutic	Surgical
		ATRA		
Carmont et al. [9]	2017	III	Therapeutic	Surgical
Ecker et al. [13]	2016	IV	Therapeutic	Non-operative
Carmont et al. [8]	2015	I	Prognostic	Surgical
		HRH		
Willy et al. [75]	2017	II	Prognostic	Surgical versus non-operative
Olsson et al. [50]	2014	II	Prognostic	Surgical versus non-operative
Silbernagel et al. [62]	2010	II	Prognostic	Surgical versus non-operative
		ROM		
Tengman et al. [68]	2013	III	Prognostic	Non-operative
Mezzarobba et al. [43]	2012	IV	Prognostic	Surgical
Hufner et al. [24]	2006	IV	Therapeutic	Non-operative
Wagnon et al. [71]	2005	III	Therapeutic	Surgical
McComis et al. [41]	1997	III	Therapeutic	Non-operative

NS: not specified. Values expressed as means and standard deviations or means and ranges. Number of participants between brackets corresponds to subjects lost to follow-up or excluded from final analysis.

FOLLOW-UP (MONTHS)	N =				AGE (YEARS)
	PARTICIPANTS	MALES	PATIENTS	HEALTHY CONTROLS	
		MRI			
168 ± 6	55	48	55	0	38 ± 8
91 ± 31.3	52	41	52	0	48.6 ± 8.7 (23-55)
		US			
43.5 ± 12 (27-69)	20	16	20	0	45.6 ± 12 (24-63)
73.2 ± 24	34	31	34	0	48.6 ± 9.5 and 47.9 ± 12.4
6	27 [2]	21 [NS]	27 [2]	0	39 ± 11
73.2 ±24	34	31	34	0	41 (30-50) and 48 (42-72)
72 ± 6	22	16	11	11	34.5 ± 8,3
43 ± 12.4 (24-72)	20	16	20	0	45.6 ± 12.3
12	9	6	4	5	48 ± 8
12	18	12	8	10	46 ± 13 and 28 ± 8
		RADIOGRAPHY			
168 ± 6	55	48	55	0	39 ± 9 and 38 ± 7
52	35	30	35	0	38.2 and 43.8
18	30	25	30	0	NS
52	60	53	60	0	38.3 ± 9.2 and 38.3 ± 7.6
15 ± 1.6	50	47	50	0	35 (21-55) and 37 (23-53)
12	10	8	10	0	39 (29-48)
16	71 [10]	51 [NS]	71 [10]	0	39 (24-63) and 35 (20-73)
		ATRA			
12	70 [5]	58 [53]	70 [5]	0	44 (29-64) and 47.6 (28-77)
27 ± 20 (12-88)	114	NS	114	0	40 ± 9 (22-65)
12	26	17	26	0	42 ± 8
		HRH			
73.2 ± 24	34	31	34	0	48.6 ± 9.5 and 47.9 ± 12.4
12	93 [17]	79	93 [17]	0	39.7 ± 9.3
12	78	65	78	0	42 ± 9
		ROM			
39.6 ±10.8 (24-60)	52	43	52	0	49.2 (26-68)
24	40	38	21	19	42.8 ± 7.9
66 (12-152.4)	125	105	125	0	39.8 (19.9-69.8)
40 (12-105)	57	48	57	0	43 (24-76)
31 (24-45)	30	26	15	15	42 (33-62) and 43 (32-67)

Five studies included healthy controls for comparison with injured patients [26, 41, 43, 64, 67], and three of these matched their controls with injured patients [26, 41, 43]. All the studies that relied on clinical parameters to assess tendon lengthening included the healthy limb as comparison [8, 9, 13, 24, 41, 43, 50, 62, 68, 71, 75]. Ten of the studies that relied on imaging methods (n = 17) to assess tendon length included comparisons with the healthy limb [1, 7, 22, 26, 38, 55, 57, 64, 67, 79]. The other 7 studies were radiographic measurements of tendon lengthening relying on metal markers, implanted in the tendon at the time of treatment, and measurements were made sequentially, providing an actual measurement of progressive tendon elongation [21, 28, 45, 52, 58–60].

Most studies used US to assess tendon length (n = 8) [1, 7, 26, 38, 55, 64, 67, 79], followed by metal markers and radiography (n = 7) [21, 28, 45, 52, 58–60], ROM (n = 5) [24, 41, 43, 68, 71], HRH [50, 62, 75] and ATRA [8, 9, 13] (n = 3, each), and MRI (n = 2) [22, 57].

Risk of Bias

A summary of the risk of bias across studies according to the QUIPs tool is shown in Figure 30. The risk of bias in individual studies is shown in Table 13.

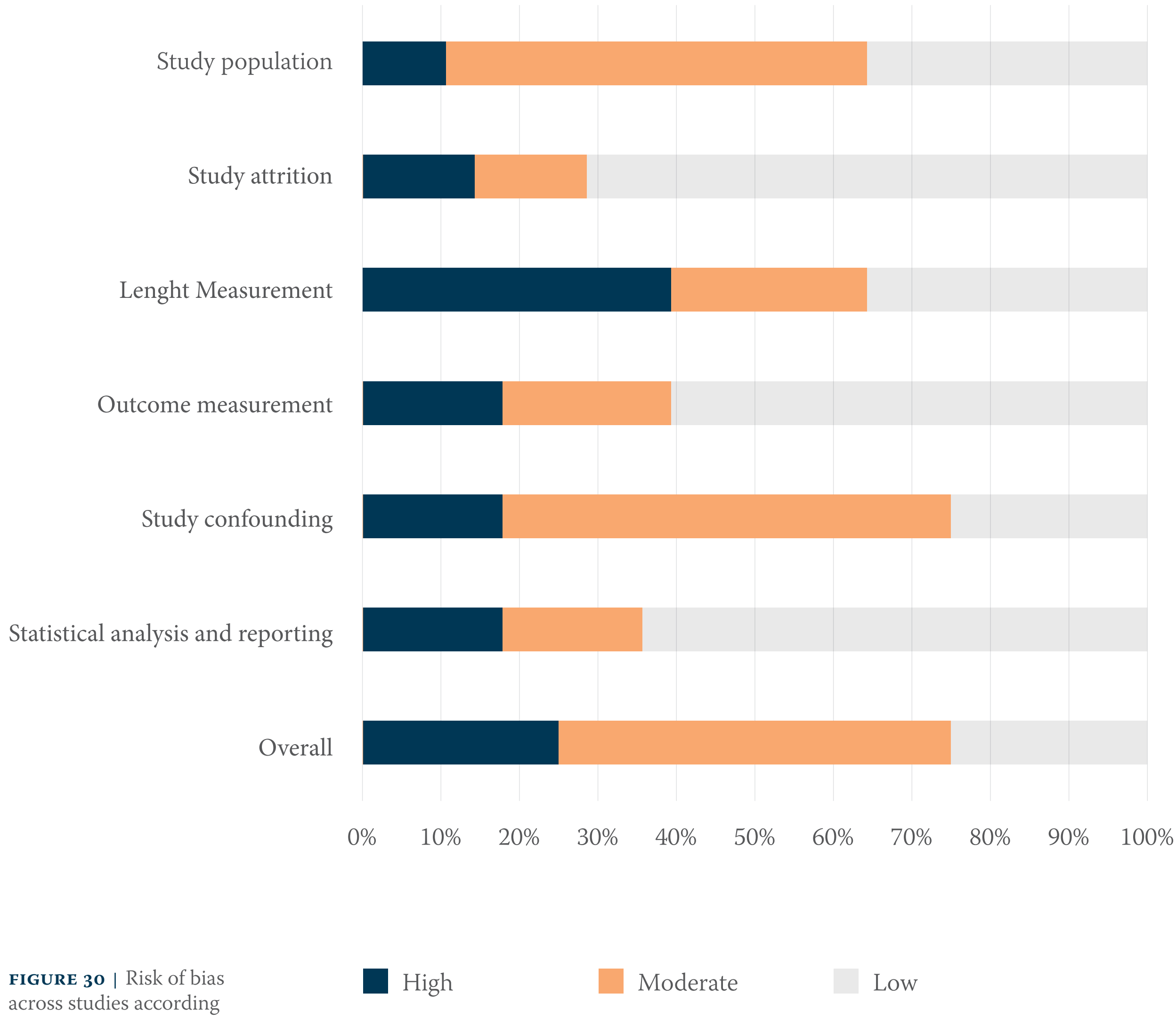

FIGURE 30 | Risk of bias across studies according to the adapted QUIPs tool.

TABLE 13 | RISK OF BIAS IN INDIVIDUAL STUDIES

AUTHORS	YEAR	STUDY POPULATION	STUDY ATTRITION	TENDON LENGTH MEASUREMENT
		PROMs		
Carmont et al. [9]	2017	Moderate	Moderate	High
Olsson et al. [50]	2014	Moderate	Moderate	High
Manegold et al. [38]	2018	Moderate	Low	Low
Zellers et al. [79]	2018	Moderate	High	Low
Heikkinen et al. [21]	2016	Low	Low	Moderate
Carmont et al. [8]	2015	Moderate	Low	High
Schepull et al. [58]	2013	Low	Low	Moderate
Schepull et al. [60]	2012	Moderate	Low	Moderate
Silbernagel et al. [64]	2012	Moderate	Low	Low
Silbernagel et al. [62]	2010	Moderate	Moderate	High
		STRENGTH AND POWER		
Heikkinen et al. [22]	2017	Moderate	Low	Low
Pajala et al. [52]	2009	Low	Low	Moderate
Mccomis et al. [41]	1997	Moderate	Moderate	High
Ecker et al. [13]	2016	Low	High	High
Heikkinen et al. [21]	2016	Moderate	Low	Moderate
Mortensen et al. [45]	1999	Moderate	Low	Moderate
		BIOMECHANICS		
Manegold et al. [38]	2018	Moderate	Low	Low
Powell et al. [55]	2018	Low	Low	Low
Brorsson et al. [7]	2017	Low	Low	Low
Jandacka et al. [26]	2017	Low	High	Low
Willy et al. [75]	2017	Low	Low	High
Agres et al. [1]	2015	Moderate	Low	Low
Tengman et al. [68]	2013	Moderate	Low	High
Mezzarobba et al. [43]	2012	High	Low	High
Zellers et al. [79]	2018	Moderate	High	Low

OUTCOME MEASUREMENT	STUDY CONFOUNDING	STATISTICAL ANALYSIS AND REPORTING	OVERALL
PROMs			
Low	High	Low	High
Low	Low	Low	Moderate
Low	Moderate	Low	Low
Moderate	Low	Low	Moderate
Low	Moderate	Moderate	Moderate
Low	Low	Low	Low
Low	Moderate	Moderate	Moderate
Low	Moderate	Moderate	Moderate
Low	Moderate	Low	Low
Low	Low	Low	Moderate
STRENGTH AND POWER			
Low	Low	Low	Low
Moderate	Moderate	Low	Moderate
Moderate	High	Low	Moderate
High	Moderate	Low	High
Low	Moderate	Moderate	Moderate
High	Moderate	Low	High
BIOMECHANICS			
Moderate	Moderate	Low	Moderate
Low	Moderate	High	Moderate
Low	Moderate	Low	Low
Moderate	Moderate	High	Moderate
Low	Low	High	Moderate
Moderate	Moderate	Low	Moderate
Low	High	High	High
Moderate	Moderate	High	High
High	Low	Low	High

Findings

Findings were grouped into four categories: **PROMs** (n = 10) [8, 9, 21, 38, 50, 58, 60, 62, 64, 79], **strength and power** evaluations (n = 5) [13, 21, 22, 45, 52], **biomechanical** tests (n = 10) [1, 7, 26, 38, 41, 43, 55, 68, 75, 79], and **other** outcome measures (n = 19) [7–9, 13, 21, 22, 24, 28, 38, 45, 57, 59, 62, 64, 67, 71, 79]. Data related to tendon length, tested correlations and/or biomechanical tests, with comments, are shown in Table 14.

TABLE 14 | STUDY FINDINGS

AUTHORS	YEAR	VALUES	TESTED STATISTICAL CORRELATIONS	COMMENTS
		MRI		
Heikkinen et al. [22]	2017	CTG: 19.9 cm for the injured *versus* 18.7 cm for the healthy side (mean difference of 1.2 cm [6%], 95% confidence interval [CI] = 0.86 to 1.56 cm; p < 0.001).	Isokinetic strength, calf muscle volume	A significant correlation was found between the difference in length of the injured and healthy Achilles tendons and the ankle end-range plantar flexion strength deficit (r = 0.38 to 0.51, p < 0.001 to p = 0.006) and also with the soleus (r = 0.42, p = 0.002) and medial gastrocnemius (r = 0.46, p = 0.001) muscle volume deficits. Furthermore, negative correlations between flexor hallucis longus muscle volume and mid-range plantar flexion strength deficits (r = – 0.37 and – 0.38, p = 0.008 and 0.006) and the difference in Achilles tendon length (r = – 0.30, p = 0.031).
Rosso et al. [57]	2013	CTG: 19.84 ± 2.41 cm for the injured *versus* 18.06 ± 2.50 cm for the healthy side (p = 0.0001).	Calf muscle volume, ROM	No correlation was found between MV and Achilles tendon length, when comparing injured and healthy sides, but a 17% deficit in triceps surae MV and marked fatty infiltration was found when comparing with the healthy limb. A weak correlation between clinically measured ankle dorsiflexion and Achilles tendon length was found (r = 0.07, p = 0.008).
		US		
Manegold et al. [38]	2018	CTG: 21.33 ± 2.94 cm (13.78-26.9) for the injured *versus* 19.85 ± 2.18 cm (15.35-26.38) for the healthy side (p = 0.009).	ATRS, Hannover score, VAS, TAS, MCC, ROM during walking, passive ROM.	No correlation between tendon length changes, as absolute or relative values, and PROMs or clinical measurement of ROM using a goniometer. A correlation was found between AT length asymmetry and MCC. Patients experienced a significant reduction in PROMs when MCC asymmetry exceed 2 cm. Asymmetry regarding AT length also correlated with biomechanical side-to-side differences in dorsiflexion (r = 0.428, p = 0.034) and plantarflexion (r = -0.435, p = 0.028) as measured during level walking, and in eversion (r = 0.441, p = 0.026) and inversion (r = -0.385, p = 0.047) during upstairs walking.

Continuation of table 14

AUTHORS	YEAR	VALUES	TESTED STATISTICAL CORRELATIONS	COMMENTS
Powell et al. [55]	2018	CTG: 22.7 (20.9-24.6) cm for the injured *versus* 21 (19.3-22.7) cm for the healthy side ($p < 0.001$; LSI: 108.6% 95% CI: 105.6-111.7).	None specified	The authors found a "pattern of greater lower extremity impact forces and greater eccentric knee power, perhaps as a compensation for reduced ankle powers, during a drop countermovement jump". The injured limb had a 39.6% higher loading rate of vertical ground reaction force ($p < 0.001$, 95% CI: 122,7-156,5%), 21.6% less eccentric ankle joint power ($p < 0.001$, 95% CI: 70.6-86.2%) and 16.8% higher eccentric knee joint power ($p = 0.008$, 95% CI: 106.8-126.9%). There also was a 19.9% deficit in concentric ankle joint power ($p < 0.001$, 95% CI 74.7-85.%). Participants also jumped 12.9% lower with the injured limb ($p < 0.001$, 95% CI: 83.0-92.8%).
Zellers et al. [79]	2018	CTG: 22.3 ± 2.7 cm for the injured *versus* 20.6 ± 2.7 cm for healthy side ($p < 0.001$).	PAS, gait speed, step counts, HRW	No correlation was found in relation to PAS, gait analysis or step counts. Tendon elongation at 8 weeks ($r = -0.602$, $p = 0.005$) and 12 weeks ($r = -0.589$, $p = 0.008$) correlated negatively to HRW at 24 weeks.
Brorsson et al. [7]	2017	CTG: 23.7 ± 2,4 (18.0-27.8) for the injured *versus* 21.6 ± 2,2 (16.7-26.1) for the healthy side ($p < 0.001$).	Kinematic and kinetic variables; HRH	A significant correlation between tendon length and peak ankle abduction during walking ($r = 0.38$; $p = 0.027$) and jogging ($r = 0.43$; $P = 0.015$), and between peak angle abduction and HRW ($r = 20.37$; $p = 0.036$) was found. No significant correlations were noted between the kinetic variables (eccentric and concentric plantar flexor power, peak Achilles tendon force and Achilles tendon impulse) and tendon length ($P = .077-.969$). There also was a negative correlation between tendon length at 6 years and HRH LSI ($r = -0.41$; $p = 0.018$).
Jandacka et al. [26]	2017	CTG, difference between sides: 1.69 ± 0.92 cm in patients *versus* 0.29 ± 0.23 cm in controls ($p = 0.000$).	None specified	The authors noted that athletes with previous Achilles tendon ruptures "reduced ankle range of motion during second half of the stance phase of running (Δ7.6°), an overextended knee during initial contact (Δ5.2°) and increased affected knee range of motion (Δ4.4°) during the first half of stance phase" and on the affected limb when comparing to the healthy control group. There also was a greater higher maximum net hip extension moment on the healthy limb.
Agres et al. [1]	2015	CTG: 21.33 ± 2.94 cm for the injured *versus* 19.8 ± 2.18 cm for the healthy side ($p = 0.009$).	ROM and gait analysis	Intra-patient ratios of AT length correlated negatively with maximum dorsiflexion angle ($r = -0.514$, $p = 0.010$) and positively with maximum eversion angle ($r = 0.386$, $P = 0.046$) during gait. The authors found no significant correlations between intra-patient ratios of AT length and ankle moment parameters.

Continuation of table 14

AUTHORS	YEAR	VALUES	TESTED STATISTICAL CORRELATIONS	COMMENTS
Suydam et al. [67]	2015	Difference between the tendon length of the injured and healthy sides was 3.6± 0.8cm (p < 0.01) at 6 months, and 3.1±0.1cm (p = 0.01) at 12 months.	EMG activity	A moderate correlation was found between Achilles tendon length and iEMG of the lateral gastrocnemius (r = 0.52, ns) and a fair correlation for the medial gastrocnemius and soleus muscles (r = 0.38, ns; r = 0.49, ns, respectively). No correlation was found between Achilles tendon length and iEMG of the Achilltes tendon (r < 0.01, ns).
Silbernagel et al. [64]	2012	CTG: 22.1 ± 2.9 cm for the injured *versus* 19.4 ± 2.6 cm for the healthy side (p = 0.017).	HRH, ATRS, FAOS	A negative correlation was found between limb asymmetries in HRH and tendon length at 6 and 12 months (r = -0.943 and p = 0.002, and r = -0.738 and p = 0.037, respectively). A negative correlation between the degree of tendon elongation and the ATRS (r = -0.928, p = 0.008) and the Sport subsection of FAOS (r = -0.899, p = 0.015) was also found at the 6-month evaluation. This correlation was not found at the 12-month evaluation (r = -0.515, p = 0.192, and r = -0.674, p = 0.097).
RADIOGRAPHY				
Heikkinen et al. [21]	2016	Mean elongation was 1.27 cm in the nonaugmented repair group and 1.45 cm in the augmented repair group.	Isokinetic strength, Leppilahti score and RAND-36	No correlation was found between Achilles tendon elongation and any isokinetic strength parameter or clinical result at 14 years follow-up.
Schepull et al. [58]	2013	Mean separation of markers between weeks 7 and 52: 0.15 ± 0.33 cm in early tensional loading patients and 0.18 ± 0.52 cm in patients managed with immobilization and early weightbearing. Two outliers with an elongation of 2.8 and 3.1 cm were excluded from the average.	ATRS	The outliers had an "acceptable ATRS value (76 and 84)", but had a lower than average HRH LSI (17 and 38). However, overall, even if these patients were included, the authors found "no significant correlation between elongation and clinical results".
Schepull et al. [60]	2012	Between weeks 3 and 7 the markers separated a median of 3.1 mm and between weeks 7 and 19 a median of additional 4.7 mm. Between 7 weeks and 18 months, the authors observed a slight reapproximating of 0.7 mm.	ATRS	No correlation was found between the occurrence of tendon elongation and the functional outcome at 18 months.

Continuation of table 14

AUTHORS	YEAR	VALUES	TESTED STATISTICAL CORRELATIONS	COMMENTS
Pajala et al. [52]	2009	Median separation of markers at 12 months: 10 mm in the simple repair group and 5 mm in the augmented group.	Isokinetic peak torque deficits and isometric strength deficits in the simple repair group	A correlation was found between tendon elongation and isometric strength deficits (r = 0.475, p = 0.026), and isokinetic peak torque deficits at 120 degrees/sec (r = 0.52, p = 0.013) and 180 degrees/sec (r = 0.64, p = 0.001) in the simple repair group. No explicit conclusion is specified for the augmented group. The results in terms of the subjective and objective ankle outcomes, the isokinetic strength scores, the mean peak work-displacement relationships, and tendon elongation were similar in both groups.
Kangas et al. [28]	2007	Mean separation of markers at average follow-up of 60 weeks: 2.0 (–2.0-5.5) mm in early motion patients and 5.0 (2.0-10.0) mm in patients managed with early immobilization in tension.	Leppilahti score, isokinetic and isometric strength	The authors found a negative correlation between tendon elongation and clinical outcome (r = -0,42; p = .017), but not with isokinetic peak torque values or isometric strength.
Schepull et al. [59]	2007	Mean separation of markers between 6 and 52 weeks was 0.35 (0.93-1.12) cm.	HRH	The authors found no significant correlation between changes in tendon length from 6 weeks to 12 months and HRH LSI (r = -0.43, p = 0.26).
Mortensen et al. [45]	1999	Median separation of markers at 12 weeks: 11.5 (0-33) mm in the early motion patients managed *versus* 9 (1-41) mm patients managed with casting.	Isometric strength, HRH	No correlation between separation of markers and strength tests performed with the isometric strain-gauge (r = 0.12; p = 0.38) or dynamic muscle function tested with the heel-rise device (r = 0.03; p = 0.82) was found. Increased dorsiflexion or dorsal shift in ankle ROM was found in 11 patients (median separation of the markers was 8 mm at 12 weeks).
ATRA				
Carmont et al. [9]	2017	Mean ATRA difference at 3 months was on -7.0 ± 5.3 degrees, and at 12 months: was -5.2 ± 3.9 degrees.	HRH, HRW and ATRS	The authors found a correlation between the ATRA at 3 months and 12 months following surgery and the HRH LSI at 12 months (r = 0.617, p < .001 and r = 0.535, p < .001, respectively). A correlation between ATRA at 3 months and 12 months and the ATRS at 12 months was also found in both groups (Group 1: r = 0.624, p = 0.006 and r = 0.588, p = 0.01; Group 2: r = 0.421, p = 0.06 and r = 0.367, p = 0.018).
Ecker et al. [13]	2016	Relative ATRA at 12 months: no difference in 39 patients, 1-5 degrees in 46, 6-10 degrees in 23, 11-15 degrees in 4, 16-20 degrees in 2.	HRW, MCC	A negative correlation tendon length and HRW LSI (r = -0.3) was found. There was also a negative correlation between tendon length and MCC (r = -0.5) and between MCC and HRW LSI (r = -0.3).

Continuation of table 14

AUTHORS	YEAR	VALUES	TESTED STATISTICAL CORRELATIONS	COMMENTS
Carmont et al. [8]	2015	Relative ATRA at 6 weeks was 2.6 ± 6.2 degrees and at 3 months was -6.5 ± 6.5 degrees.	ATRS, HRH	Absolute ATRA correlated, at 12 months, with HRH LSI (r = -0.63, p = 0.002, N = 22), and at 3 and 6 months with the ATRS (r = 0.63, p = 0.001, N = 26 and r = 0.46, p = 0.027, N = 23, respectively). There were no significant changes in ATRA after 3 months.
HRH				
Willy et al. [75]	2017	Mean values for the injured and uninjured limbs were 10.5 (95% CI: 9.7-11.3) cm versus 12.7 (95% CI: 12.1-13.2) cm, respectively (p < 0.001).	None specified	Generalized HRH deficits were found (p < 0.001; d = -1.05; LSI: 82.7%). The authors observed "Considerable side-to-side deficits in plantarflexor function" during walking, hopping and jumping. Also noted were, possibly compensatory, increased knee joint loads, but only during jogging and hopping.
Olsson et al. [50]	2014	LSI of HRH: 81 ± 14% in males, and 70 ± 17% in female (p = 0.024).	ATRS	Using a multiple linear regression model, HRH at 6 months was found to be predictive of symptoms (ATRS) at 12 months (r^2 = 0.5, p = 0.008, 95% CI: 13.65-85.69) for male patients. Heel-rise height at 6 months was found to predict the degree of symptoms at 12 months (Table 6). The authors noted that "a 10% higher heel-rise height at 6 months predicted a 5-point increase in the ATRS". Using univariate analysis HRH LSI at 6 months correlated with the ATRS at 12 months (r = 0.26, p < 0.001).
Silbernagel et al. [62]	2010	Mean values for the injured and uninjured limbs at 6 months were 10.2 *versus* 14.1 cm, and at 12 months were 11.1 *versus* 13.9 cm, respectively (p < 0.001).	ATRS, ROM	A significant correlation was found between both HRW and HRH LSI and the ATRS at 6 months, but no other significant correlations were found at either the 6- or 12-months evaluations.
ROM				
Tengman et al. [68]	2013	Maximum ankle dorsiflexion with bent knee: 15.7 ± 5,2 in the injured *versus* 14.9 ± 6,3 in the healthy side (p = 0.437); with straight knee: 11.1 ± 4.8 degrees in the injured *versus* 9.2 ± 5.9 degrees in the healthy side (p = 0.02).	None specified	Total range of motion was similar in injured and healthy sides. Gait analysis revealed reduced plantar flexion on the injured side during stance phase, implying dorsal shift in foot position. Furthermore, peak dorsiflexion was delayed and the angle at toe-off was lower on the injured sided during walking. Patients' ATRS correlated with kinematic parameters of the ankle on the injured side (plantar flexion in loading response correlation coefficient [CR], 0.366, P .0.008; peak dorsiflexion CR, 0.341, P . .013; dorsiflexion during terminal swing CR, 0.277, P .0.049).

Continuation of table 14

AUTHORS	YEAR	VALUES	TESTED STATISTICAL CORRELATIONS	COMMENTS
Mezzarobba et al. [43]	2012	Difference between limbs regarding ankle dorsiflexion ROM was greater in the injured group (4 ± 2.87 degrees) than in the control group (2 ± 0.27 degrees) ($p = 0.0063$).	None specified	The authors noted a significant reduction of the maximum plantarflexion angle of the injured leg versus the healthy leg (−9 ±4.64 vs −15 ±8.15 degrees, $p = 0.01$) during 65–70% of the gait cycle. They also noted differences in maximum knee flexion (63 ±2.53 vs 61 ±4.33, $p = 0.03$) and hip extension (−16 ±4.98 vs −18 ±3.7, p 0.03). Also noted was a mild increase in the quadriceps muscle volume in the injured limb (interlimb differences in the injured and control group were significantly different, $p = 0.03$)
Hufner et al. [24]	2006	Increased ankle dorsiflexion in 21 (17%) patients.	Custom clinical score	Patients with lengthened Achilles tendons had a statistically significant ($p < 0.05$) difference in the average clinical score (73.5 ± 16 (38 to 90) points) in comparison with patients with normal tendon length (87.1 ± 9 (55 to 100) points). Patients with shortened tendons also had inferior clinical score results (79.7 (42 to 90) points), but the difference was not statistically significant ($p > 0.05$). There was a strong correlation between a lengthened Achilles tendon and a 3-cm difference in calf muscle size and impaired strength ($p = 0.01$).
Wagnon et al. [71]	2005	No precise quantification of tendon elongation or incidence.	Clinical and functional score	No correlation was found between the occurrence of tendon elongation and the clinical score ($p = 0.98$) or the functional score ($p = 0.68$).
McComis et al. [41]	1997	Between limbs difference regarding passive dorsiflexion of the ankle was a mean of 2.6 degrees greater in the injured group ($p = 0.02$).	Passive dorsiflexion and vertical force output	A correlation was found between passive dorsiflexion of the ankle and vertical force output during gait ($r = 0.40$, $p = 0.05$). The difference in vertical force output between the midstance and terminal-stance phases of gait increased with a larger range of motion in ankle dorsiflexion.

All values expressed as means and standard deviations or means and ranges, except otherwise specified. CTG: distance from calcaneal insertion of the Achilles tendon to distal myotendinous junction of the medial head of the gastrocnemius muscle. CTS: distance from calcaneal insertion of the Achilles tendon to distal myotendinous junction of the soleus muscle. PAS: physical activity scale; TAS: Tegner activity scale; VAS: visual analog scale for pain; MCC: maximum calf circumference; ROM: range of motion; HRH: heel-rise height; ATRS: Achilles tendon total rupture score; FAOS: foot and ankle outcome score; HRW: heel-rise work. LSI: limb symmetry index; ns: no statistical significance; ATRA: Achilles tendon resting angle.

Mean tendon elongation

Mean AT elongation measured using imaging techniques ranged from 0.15 to 3.1 cm (n = 17) [1, 7, 21, 26, 28, 38, 45, 52, 55, 58–60, 64, 67, 79]. Eleven studies reported mean elongations above 1.2 cm. All studies reporting mean elongations under 1 cm belonged to the radiography group (Figure 31) [21, 28, 45, 52, 58–60].

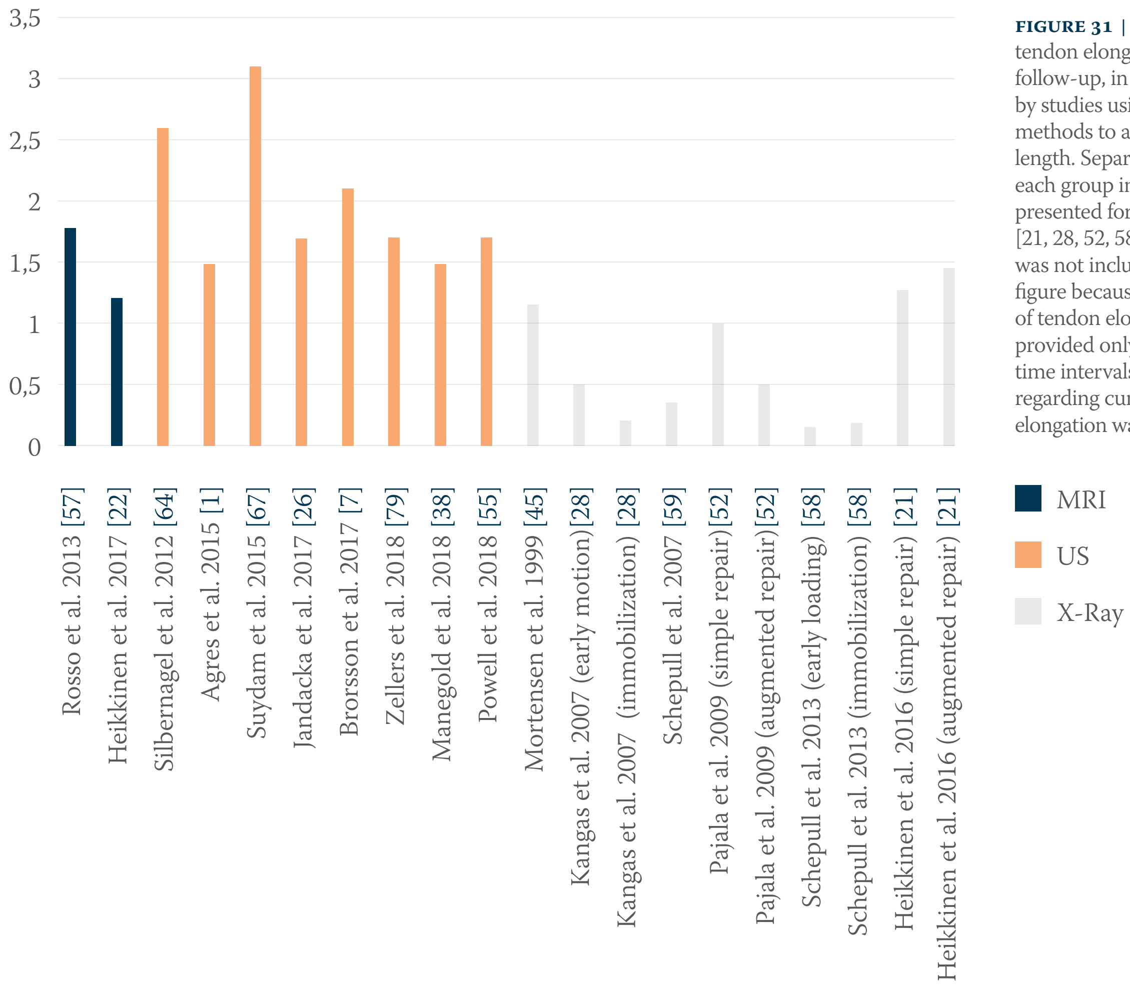

FIGURE 31 | Average tendon elongation at last follow-up, in cm, as reported by studies using imaging methods to assess tendon length. Separate values for each group in the study are presented for some studies [21, 28, 52, 58]. One study was not included in this figure because average values of tendon elongation were provided only for specific time intervals and no data regarding cumulative tendon elongation was presented [60].

Patient reported outcome measures

Of the ten studies investigating statistical correlations between tendon length or elongation and PROMs [8, 9, 21, 38, 50, 58, 60, 62, 64, 79], two found negative statistical correlations [9, 50].

In the studies basing evaluation of tendon length on imaging modalities (n = 6), none found statistical correlations at last follow-up, specifically in regard to a physical activity scale (PAS) [79], visual analog pain scale (VAS) [38], Tegner activity scale (TAS) [79], Foot and Ankle Outcome Score (FAOS) [64], Achilles Tendon Total Rupture Score (ATRS) [58, 60, 64, 79], or RAND-36 [21].

In the remaining 4 studies, basing their appraisal on ATRA or HRH, one study found a significant statistical correlation between the ATRA at 3 months and the ATRS at 12 months [9], and another study found a significant statistical correlation between the HRH at 6 months and the ATRS at 12 months [50]. The two other studies found statistical correlations between the ATRA or HRH and the ATRS at 6 months (but no statistical correlations between those outcomes were reported at 12 months) [8, 62].

Strength and power evaluations

Five studies reported strength and power evaluations and their correlation with AT elongation [21, 22, 28, 45, 52]. Two found negative statistical correlations [22, 52].

Four studies performed isokinetic measurements [21, 22, 28, 52]. One study found a correlation between the difference in length of the injured and healthy Achilles tendons and the ankle end-range plantar flexion strength deficit ($r = 0.38$ to 0.51, $p < 0.001$ to $p = 0.006$)[22]. In another study, isokinetic peak torque deficits at 120 degrees/sec ($r = 0.52$, $p = 0.013$) and 180 degrees/sec ($r = 0.64$, $p = 0.001$) were correlated with AT length [52]. In the two remaining studies, one found no correlation with any isokinetic strength parameter or clinical result at 14 years follow-up [21], and the other found a negative correlation with the Leppilahti score but not with isokinetic peak torque values [28]. The Leppilahti score is an injury-specific standardized protocol for assessment of outcomes after ATR, combining both subjective evaluation of symptoms and objective measurements, such as ankle ROM and isokinetic calf muscle strength [34].

Three studies tested for correlations between isometric strength measurements and tendon elongation [28, 45, 52]. All studies relied on radiograhic measurements. One found a correlation between tendon elongation and isometric strength deficits ($r = 0.475$, $p = 0.026$) [52]. In the two other studies no correlation between separation of markers and isometric strength [28, 45].

Biomechanical tests

Ten studies reported data related to biomechanical tests [1, 7, 26, 38, 41, 43, 55, 68, 75, 79], and nine of these found influence of tendon elongation in biomechanical parameters [1, 7, 26, 38, 41, 43, 55, 68, 75]. Five studies [1, 7, 38, 41, 79] tested for correlations between tendon length and biomechanical parameters. Four of these five studies found a significant correlation [1, 7, 38, 41].

A study by Manegold et al, found that asymmetry regarding AT length correlated with biomechanical side-to-side differences in dorsiflexion ($r = 0.428$, $p = 0.034$) and plantarflexion ($r = -0.435$, $p = 0.028$) during level walking, and in eversion ($r = 0.441$, p = 0.026) and inversion (r = -0.385, p = 0.047) during upstairs walking, despite finding no correlations with PROMs or ankle ROM measured with a goniometer [38]. Another study, by Agres et al, found that intra-patient ratios of AT elongation correlated negatively with maximum dorsiflexion angle (r = −0.514, p = 0.010) and positively with maximum eversion angle (r = 0.386, P = 0.046) during gait, but not with ankle moment parameters [1].

Brorsson et al. found a significant positive correlation between tendon length and peak ankle abduction during walking (r = 0.38; p = 0.027) and jogging (r = 0.43; P = 0.015), and between peak angle abduction and heel-rise work (HRW) (r = -0.37; p = 0.036). These authors did not find correlations regarding eccentric and concentric plantar flexor power, peak AT force and impulse [7].

McComis et al. found a correlation between passive dorsiflexion of the ankle and vertical force output during gait (r = 0.40, p = 0.05) [41]. In this study, the difference in vertical force output between the midstance and terminal-stance phases of gait increased with a larger ROM in ankle dorsiflexion, but the authors considered no loss of performance occurred [41]. Zellers et al. investigated whether tendon structural parameters were related to later walking gait symmetry, but no correlations with tendon length were reported [79].

In the remaining five studies, biomechanical evaluations were performed and comparisons between the injured and healthy limbs were made, but no statistical correlations with tendon length were investigated [26, 43, 55, 68, 75]. However, patients in these studies suffered tendon lengthening across the group, as shown by value ranges, statistical significance, confidence intervals or comparison with control groups.

All these studies found important changes in biomechanical parameters. Most notably, some studies found patterns of altered knee and hip kinematics in the injured limb: greater knee eccentric power during countermovement jump [55], overextension or increased knee ROM during running [26]; increased knee joint loads during jogging and hopping but not walking [75]; diminished maximum hip extension, differences in maximum knee flexion and mild increase in quadriceps muscle volume [43].

Other outcomes

Nineteen studies reported statistical correlations for outcomes other than PROMs, strength and power evaluations or biomechanical assessments, these were: maximum calf circumference (MCC) or muscle volume (MV)[13, 22, 38, 57], custom clinical scores [24, 71], Leppilahti score [21, 28], Hannover Score [38], step counts [79], EMG activity [67], HRW/HRW [7–9, 13, 45, 59, 64, 79], and ROM [38, 57, 62].

In the four studies that investigated correlations with MCC or MV [13, 22, 38, 57], three studies found significant negative statistical correlations between tendon length and these outcomes [13, 22, 38]. Some of these studies also found a correlation between diminished MCC/MV and worse PROMs [38] or functional evaluations [13, 22]. The remaining study did not find statistical correlations, despite finding a 17% deficit in triceps surae MV and marked fatty infiltration when comparing with the healthy limb [57].

In the two studies using custom clinical scores, one found no statistical correlations with the clinical score [71] and the other found a significant statistical correlation between increased ROM and the clinical score [24]. Two studies investigated correlations with the Leppilahti score [21, 28] and one found a statistical significant negative correlation [28]. The study reporting the Hannover Score found no correlation with tendon elongation [38].

No statistical correlation between tendon length and step count in recovering patients was found [79]. In the study investigating integrated EMG (iEMG) and AT elongation, a moderate correlation was found between AT length and muscle activation of the lateral gastrocnemius (r = 0.52) and a fair correlation with muscle activation of the medial gastrocnemius and soleus muscles (r = 0.38 and r = 0.49, respectively) [67].

In the eight studies investigating correlations between tendon length and HRH [7–9, 13, 45, 59, 64, 79], six found negative statistical correlations between tendon length, or evidence of tendon elongation, and this outcome [7–9, 13, 64, 79]. Both studies that found no correlation relied on radiographic measurements [45, 59].

In the studies assessing correlation between tendon length and ROM, statistical correlations were not found [38, 62] or were weak [57].

Summary of findings

A summary of findings for the main outcomes in relation to the influence of AT elongation is shown in Table 15.

B_f: fair evidence in favor of the impact of tendon length. C: controversial or poor evidence.

TABLE 15 | SUMMARY OF FINDINGS

CATEGORY	GRADE OF EVIDENCE
PROMs	C
Strength and Power	C
Biomechanics	B_f

DISCUSSION

Fair evidence that increased AT length imparts changes in biomechanical parameters was found. Evidence regarding a deleterious role of AT elongation in PROMs and the relationship between tendon length and functional strength evaluations was poor or controversial.

Changes caused by AT elongation are not reflected in PROMs. PROMs are important tools to assess the outcomes of interventions [5]. The ATRS is an injury specific and validated PROM, and considered the most adequate to evaluate outcomes after ATR [29, 47, 66]. Among all the PROMs included in this review, the ATRS is the only outcome measure validated specifically for this injury. Only studies using clinical methods to assess tendon lengthening have found lasting correlations with the ATRS [9, 50]. In these studies, assessment of tendon elongation at 3-6 months using the ATRA [9] or HRH [50] was found to be correlated with the ATRS at 12 months. Two other studies, also using these clinical methods to evaluate tendon elongation, reported statistical correlations between these outcomes only at 6 months [8, 62]. In the study by Silbernagel et al, HRH correlated with the ATRS at 6 months, but not at 12 months [62]. It could be argued that preserving tendon length may contribute to an earlier recovery. Both ATRA and HRH, however, may be influenced by factors other than tendon length, including capsular stiffness [8] or muscular weakness [64], and these can in turn influence the resulting ATRS. This could explain why clinical methods of assessing tendon elongation, but not measurements using imaging techniques, correlated with PROMs. It should also be considered that patient adaptation to post-injury limitations may account for a relatively high score despite lower performance [49], which may represent a bias away from higher demand activities in questions related to running, jumping, or walking quickly upstairs or uphill.

Differences in how tendon length is measured may account for discrepancies in the clinical relevance of AT elongation. Adequacy of radiographic measurements of distance between implanted metal markers is questionable, because lengthening seems to occur as well in locations outside the rupture site, as noted by Schepull et al. [59]. It is noteworthy that all studies using imaging measurements and reporting a lengthening under 1 cm used this method as a measure of tendon elongation [21, 28, 45, 52, 58–60]. Using ROM to screen for elongated tendons is probably not appropriate as well, as it should be noted that in 33 papers that were excluded because no evidence of tendon lengthening was reported, 32 relied solely on increased ankle dorsiflexion ROM. In the studies included in this review, there was no correlation between AT elongation and increased ROM, or this correlation was considered weak, when present [38, 57, 62]. Even though the most accurate measurements are given by US and MRI, it is not always practical and costs must also be factored. It should also be considered that even US can have a considerable margin of error [4]. As shown by Hansen et al, relative reliability of US measurement of AT elongation was lower than for ATRA (intra-class correlation coefficient: 0.58-0.79 *versus* ≥ 0.75, respectively) [19].

ATRA was also shown to have a lower measurement error than US. A standardized way of measuring tendon length should be adopted for research purposes. For clinical purposes, ATRA or HRH are considered adequate to assess for tendon elongation and/or muscular weakness. These measurements are part of the standardized treatment outcome assessment in the Danish Achilles Tendon Database [11].

Ability to detect strength deficits related to tendon elongation may have been impaired by inadequate strength assessment methodologies. Reporting of strength assessment after ATR has been inconsistent in the medical literature [2]. Two studies based on the same patient cohort, reached different conclusions regarding the influence of AT elongation on strength evaluations [21, 22]. Both papers come from the same research group. Only when specific joint angles were considered, specifically the ankle plantar flexion end-range, did significant correlations between strength deficits and tendon elongation become apparent [22]. A recent study by Walker et al. has shown that commonly used isokinetic strength reported outcomes are insufficient to ascertain differences between the injured and uninjured limbs in patients subjected to operative treatment of an ATR [72]. Only when a more detailed analysis was performed, did impairments in the injured limb, related to generation of end-range joint moments and sustaining of higher levels of joint moments for longer periods of time, became apparent. Differences were found mainly outside the region of the isokinetic range where the peak joint moment occurred. This means that uniquely reporting peak joint moments in isokinetic strength evaluations is inadequate. It should also be noted that in the study from Kangas et al, where no correlations with isokinetic measurements were found, very little tendon lengthening seemed to have occurred [28]. It may be the case that only higher differences will cause a difference in isokinetic strength deficits or that other factors, such increased tendon compliance [18, 42] and hysteresis [73], can influence force transmission through the tendon. Heikkinen et al reported "flexor hallucis longus muscle compensatory hypertrophy in response to a plantar flexion strength deficit and an Achilles tendon length difference" (as this muscle volume was negatively correlated with tendon length), a finding that had also been pointed out by Finni et al. [14, 22] Muscle atrophy or fat infiltration is also a common finding after ATR, and its correlation with tendon length was shown in three studies included in this review [13, 22, 38]. Incidentally, two of these studies also found a correlation between loss of MV/MCC and strength deficits [13, 22]. Future studies focusing on the influence of tendon length on strength should use a standardized method of assessing strength, probably including the angle of peak torque, reporting of values for specific joint angles and factoring time-series differences.

ATR elicits an important set of biomechanical adaptations, in what may be an effort to optimize force transmission in the lower limb. Patients with previous ATR exhibit increased knee loading during jumping and/or jogging [55, 75], increased knee range of motion and overextension of the knee on initial contact during running [26], and/or increased knee flexion and reduced hip extension during the middle stance phase of gait [43]. Also supporting these findings is the compensatory quadriceps muscle hypertrophy found by Mezzarobba et al. [43]. It should be noted that some of these changes only become apparent during higher demand tasks, like running, jumping and hopping [75]. Increased knee joint loads [23, 35] and changes in knee extension during landing may put athletes at an increased risk of knee injuries [31, 54]. Thus, high demand patients with a previous ATR should be put in specific injury prevention programs. Nonetheless, studies performing statistical correlations failed to show relevant statistical correlations with ankle moment parameters, despite finding correlations with kinematic variables [1, 7]. The need for biomechanical adaptations could help explain why 21-32% of the competitive athletes fail to return to play after acute rupture and a significant number of those who come back experience a significant reduction in performance [33, 53, 69, 70]. Consequently, it is considered that evaluation of tendon length should be part of the assessment in the results of interventions and all efforts to preserve tendon length should be made.

Limitations

This review has four main limitations. First the very nature of the question, and the type of review, made protocol design difficult. A high number of papers had to be screened and a choice was made to include therapeutic studies that also assessed for tendon elongation, meaning that these studies were not primarily aimed at assessing the consequences of tendon lengthening. This was considered a necessary compromise.

Second, almost half the studies showed moderate risk of bias and heterogeneity in the outcome assessment methods. Uniform strength evaluation methods and biomechanical analysis are needed for AT research.

Third, it was chosen to include biomechanical studies that provided no direct statistical correlations with tendon length but were composed of patients with tendon elongation across the cohort. The other studies in this group, those providing adequate statistical analysis, support this decision. More prognostic studies, using validated tendon measurement tools and appropriate statistical analysis, are needed in this regard, particularly during high demand tasks and specifically considering the influence of tendon length.

Fourth, only a small number of studies included healthy controls, and so future research should include comparisons with healthy patients to account for normal variation.

Implications for future research

Tendon lengthening causes important biomechanical adaptations that may have negative consequences in higher demand patients. It remains controversial whether tendon elongation negatively affects muscle strength. Future research should focus on the use of US/MRI tendon length measurements, uniform and adequate ankle strength evaluations, and biomechanical analysis of high demand tasks and the respective role of AT elongation. Studies with larger sample sizes are needed, in order to allow stratification of activity levels and possibly ascertaining of differences between the general population and higher demand individuals.

CONCLUSION

AT elongation after acute rupture is a relevant problem, with implications in lower limb biomechanics. Current evidence is insufficient to support, or refute, a detrimental effect of increased tendon length in PROMs or functional strength and power evaluations in a general population.

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CHAPTER 7

Modified triple Kessler with least risk of elongation among Achilles tendon repair techniques: a systematic review and network meta-analysis of human cadaveric studies

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INTRODUCTION

Achilles tendon ruptures (ATRs) are common injuries, with an incidence ranging from 6 to 31.17 per 100.000 person-years [19, 41, 45]. These injuries are 3-10 times more common in men than women, and often occur in recreational athletes aged between 30 and 40 years [19]. There is evidence that incidence is on the rise and that injuries in older patients are increasingly frequent [19, 39, 69]. ATRs are typically located between 2 and 7 cm from the calcaneal insertion, and commonly preceded by histopathological tendon changes [35].

There is ongoing debate regarding optimal management, which includes surgical and non-surgical treatment options [15, 33, 71]. Regardless of treatment choice, early weight bearing should be encouraged, as this has been shown to improve tendon healing [67, 74]. There is concern, however, that it may also lead to tendon elongation [48], particularly in the early healing period [3]. There is evidence that Achilles tendon elongation after acute rupture imparts changes in lower limb biomechanics [1, 8, 31, 47, 49, 51, 57, 72, 76] and may have a deleterious effect on end-range ankle plantarflexion strength [22]. Elongation occurs mostly in the first 6 weeks [34, 53, 81], and in surgically treated patients may be related to creeping deformation of suture material [32], suture cutting through necrotic tissue or knot slipping.

Several tendon repair techniques have been described [2, 36, 59], including augmentations with autografts/biomaterials [43]. Since early loading [82] and avoidance of tendon elongation [17] are of significant clinical importance, prioritizing surgical techniques in accordance with their ability to withstand loading at time-zero, i.e. immediately after repair and before significant tendon healing has occurred, is of great research interest. Furthermore, summarizing the techniques' loading ranges allows for adequate programming of rehabilitation protocols and an improved understanding of failure mechanisms can foster development of new surgical techniques and/or materials.

The primary aim of this study was to systematically review the literature regarding tensile strength and tendon elongation with cyclic loading of Achilles tendon repair techniques at time-zero, in cadaveric models, and, if appropriate, perform a network meta-analysis (NMA) to rank these surgical techniques according to the aforementioned outcomes, together with an evaluation of statistical correlations. The secondary aim of this study was to investigate failure mechanisms and statistical correlations between these and rankings of tensile strength and resistance to tendon elongation.

MATERIALS AND METHODS

This systematic review is reported according to the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) guidelines and PRISMA NMA extension [29, 52].

Literature search

PubMed, CENTRAL and Web of Science were searched for all published articles. No time restrictions were applied. Relevant references extracted from the articles screened were also included for analysis. Searches were conducted on March 12th of 2021.

The following search string was used: (((Achilles OR calcaneal OR calcaneus OR calcanean) AND (tendon OR tendo)) OR (tendoachilles OR tendocalcaneus)) AND (repair OR suture* OR surgery) AND (biomechanical OR mechanical OR cadaver* OR "in vitro").

Study selection

All *in-vitro* studies using human cadaveric Achilles tendons, comparing rupture repair surgical techniques or augmentation procedures using autografts/biomaterials, and reporting failure load or measurement of elongation after cyclic loading, were eligible for qualitative evaluation. Only studies with randomized specimen allocation, or using matched pairs, and with clear descriptions of the surgical techniques were considered adequate for quantitative synthesis.

Studies exclusively reporting comparisons of suture materials, technique modifications, or epitendinous weave augmentations were excluded, as were studies mixing specimens from different anatomical locations, or where only one end of the tendon was used in mechanical testing. Also excluded were studies related to surgical reattachment of the Achilles tendon to the calcaneus, treatment of chronic injuries and reconstruction of tendon defects. Systematic reviews were used only to identify primary studies. Narrative review papers and expert opinions were excluded. Due to limitations of the research team regarding languages spoken and access to translators, only articles in English, Dutch, French and Spanish were considered eligible for inclusion.

From title and abstract, all studies reporting results of *in-vitro* mechanical testing of Achilles tendon repairs in human cadaveric specimens were selected for full-text appraisal. Relevant references from full texts were screened for eligible papers. Two reviewers independently screened and selected studies for full text analysis from title and abstract using the Rayyan QCRI systematic review management app [56]. Disagreement was settled by discussion. A third reviewer was consulted for arbitration if disagreement persisted.

Data extraction

Customized forms, Microsoft Excel and Rayyan QCRI were used for data management. Both reviewers performed data collection, in duplicate, and data was cross verified afterwards.

The following data items were collected: authors, year of publication, number of specimens, average age, number of males and females, method used to create rupture, surgical techniques, suture material, number of cycles in cyclic loading, loading protocol, construct failure definition, failure load, measurements of elongation after cyclic loading, failure mechanism, other technical or outcome data available, and funding sources.

Primary outcomes were failure load and elongation after cyclic loading. Failure load was considered to be the maximum load value, in Newtons, that a repair construct could withstand as a result of progressive uniaxial stretching. Elongation after cyclic loading was considered to be the measured gap, in millimeters, between tendon ends, or equivalent construct elongation, after a *x value* of cycles, regardless of load values or number of cycles. If a study performed a sequential loading protocol for survival analysis, the loading block with highest load applied, while still including all repairs from all testing groups, was selected.

A secondary outcome was the evaluation of the failure mechanisms for each of the included repair techniques. These were categorized into three groups: failure at suture-tendon interface, at suture or scaffold, and other mechanisms of failure.

Risk of bias in individual studies

The methodological quality at study level was assessed using a risk of bias assessment tool developed for this study. This tool was based, regarding structuring in domains and issues, on the Quality in Prognostic Studies tool [21], but the specific domains and issues were defined specifically for the purposes of this study. Domains assessed and issues considered can be found in Table 16. For each study, an overall risk of bias, set at low, medium or high risk, was determined and later used for confidence assessment of NMA findings.

TABLE 16 | APPRAISAL OF RISK OF BIAS IN INDIVIDUAL STUDIES

DOMAINS	ISSUES CONSIDERED
Specimen selection	If specimens were matched pairs. If specimens came only from elderly cadavers. If specimens with signs of previous injury were stated to be excluded.
Specimen preparation	If there was an adequate description of specimen preparation. If specimens were randomly allocated to the techniques when applicable.
Repair techniques and materials	Suture material brand specification and adequate description of techniques. If different suture materials were used for different techniques.
Testing procedures	Clear definition of failure should be provided. Adequate description of loading protocol, location of tenotomy or injury preparation.
Statistical analysis and data reporting	If number of specimens needed was defined by statistical methods. Appropriate reporting of mean/median, standard deviations and confidence intervals. Adequacy of statistical tests and statement of statistical significance levels.

Domains assessed, and issues considered in the risk of bias appraisal in individual studies.

Statistical analysis

Statistical analysis was performed using Microsoft Excel v16.45 (Microsoft, Redmond, WA, USA) and R (R version 3.6.1 GUI 1.70, Vienna, Austria) [58]. Statistical significance was set at $p < 0.05$.

Primary outcomes

Network meta-analysis was used for direct and indirect comparison of studies in relation to the primary outcomes. This is a quantitative synthesis tool that allows direct and indirect comparisons between treatments [44]. While meta-analysis has traditionally been used to carry direct pairwise comparisons, NMA can perform indirect comparisons between interventions by using a common comparator [42], i.e. if treatments A and B are compared with treatment C, then treatments A and B can be compared *through* treatment C. In addition to many of the requirements of standard pairwise meta-analysis [25], researchers must ensure that the transitivity assumption is respected in order to conduct an NMA [9]: patient/subject characteristics and methodologies of studies making different direct comparisons should be sufficiently similar, except regarding the interventions being compared [65].

A frequentist random effects framework was employed, using the *netmeta* package [60] in R. Comparisons were made using difference between means and 95% confidence intervals. These were summarized as a ranking using the P-score. The P-score is a technique proposed by Rücker et al. and is the frequentist model equivalent of the Surface Under the Cumulative Ranking curve (SUCRA) of Bayesian networks [62]. The latter is a statistical measure described by Salanti et al. that summarizes the relative probability of a given technique being among the best option in the selected outcome [64]. *Specimen* was defined as the unit-of-analysis [26].

After removal of techniques not present in both networks, the Spearman's Rank correlation coefficient was used to investigate if a correlation between ranking positions existed.

Network meta-analysis

Networks of repair techniques were constructed for the two primary outcomes. Assumptions regarding geometry of networks can be found in Table 17. It was considered that experiments were conducted in similar conditions, and that repairs were performed according to current surgical technique standards. In short, it was considered that no significant effect modifiers were present, thus meeting the transitivity assumption.

TABLE 17 | ASSUMPTIONS REGARDING GEOMETRY OF NETWORKS

GROUPED IN THE SAME NODES	ALLOCATED TO DIFFERENT NODES
1. variations of one specific technique (for example Krackow and "Giftbox" Krackow stitches) were grouped together in a single node. 2. Differences in suture types, and caliber, between studies using the same technique were disregarded. 3. Repairs with epitendinous weave reinforcements were put in the same nodes as those without them.	1. Techniques with doubled strands (double or triple Kessler, double Krackow and double Bunnell) were placed in different nodes from the original techniques. 2. Minimally invasive techniques were also placed in separate nodes, because of existing technical differences (for example: number of strands, anchor fixation, and cross-locked configurations). 3. Krackow repairs augmented with biomaterials were put in different nodes due to morphological and material differences between them.

Assumptions regarding geometry of networks.

The possibility of reporting bias was assessed using a funnel plot and Egger's test. Statistical heterogeneity was evaluated using the I^2 and an equivalent of Cochran's Q tests [37]. In case of high heterogeneity, the source was investigated and a decision made as whether to proceed, or not, with the NMA. For the purposes of this review, the clinically important effect was determined using a distribution-method approach, concretely 0.5 standard deviations (SD) from all repairs in each network [55]. Incoherence was assessed using the node splitting approach [16], with the *netsplit* function in *netmeta* [70], and visually with a net heat plot function called *netheat*, which was used to locate incoherence within networks [38]. A design-by-treatment X^2 test was used to evaluate if the assumption of coherence was held for the entire network [65].

Missing values were dealt with in accordance with technical recommendations from the *Cochrane Handbook for Systematic Reviews of Interventions* [26]. Specifically, missing standard deviations were obtained using differences between means and P values.

Subgroup sensitivity analysis was also performed. It was considered how selecting only studies using matched pairs or excluding studies with specimens from persons aged more than 70 years old (studies not reporting specimen age were still included) would change the P-score ranking of the techniques. It was also considered whether separating the "Giftbox" Krackow from standard Krackow repairs and separating techniques with an epitendinous weave augmentation into different nodes would change the P-score ranking. Finally, it was investigated whether the inclusion of studies investigating augmentation procedures using biomaterials/autografts contributed significantly to statistical heterogeneity in the failure load NMA.

The *web app* CINeMA [65] was used for assessing confidence in the NMA results. This methodological framework, described by Salanti et al, considers six domains: within-study bias (based on the previous appraisal of risk of bias in individual studies), reporting bias, indirectness, imprecision, heterogeneity and incoherence.

Secondary outcome

For the secondary outcome, data was pooled into a database and summarized as percentages for each failure mode category. For each NMA, Pearson's r was used to explore a potential correlation between percentage of repairs failing by disruption of the suture-tendon interface and P-score of each technique. The same statistical evaluation was performed for percentage of repairs failing due to suture/scaffold breakage.

RESULTS

The search strategy yielded 2949 entries. Sixteen studies met the inclusion criteria for quantitative synthesis [5, 6, 10, 12, 14, 18, 20, 23, 24, 28, 30, 46, 50, 54, 75, 77]. The study search and selection flowchart, with reasons for exclusion, is shown in Figure 32. A list of full-text papers, with justifications for exclusion, is provided in Appendix II (Table II-A).

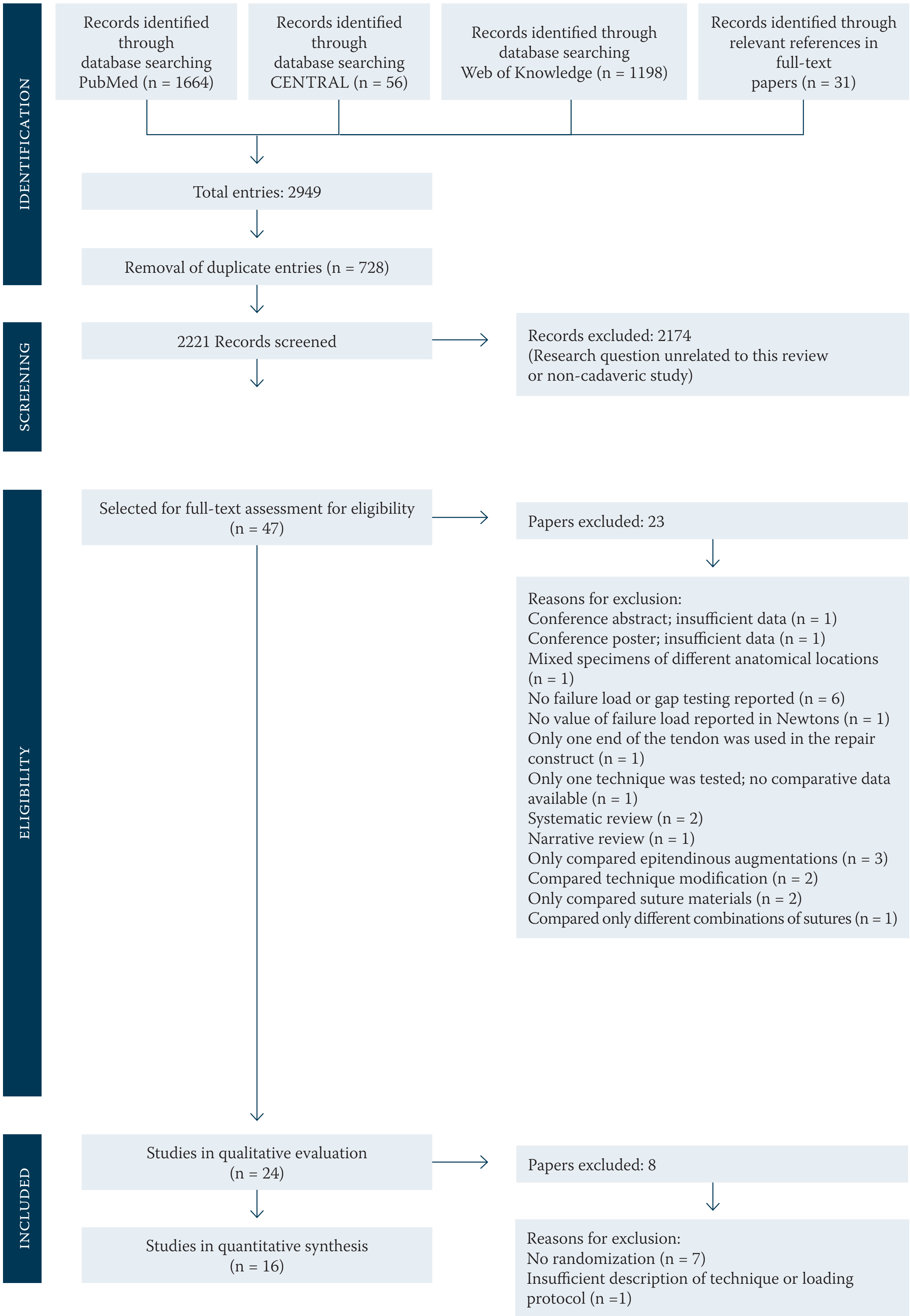


FIGURE 32 | PRISMA flowchart.

General study characteristics

General study characteristics is shown in Table 18. Total number of specimens included was 367. Three techniques/studies used epitendinous reinforcements: modified triple Kessler [10], one study containing Bunnell and Krackow (consisting of a "Giftbox" Krackow variation) repairs [75] and MFSS [54].

TABLE 18 | GENERAL STUDY CHARACTERISTICS

STUDY	N	AGE	% MALES	TECHNIQUES	LOADING PROTOCOL	MATERIALS	OUTCOMES
COMPARISONS OF SUTURE TECHNIQUES							
Frosch et al. (2020) [18]	16	89.75 (±5.75)	37.5%	Kessler, DLKS	Loaded for 1000 cycles from 5 to 20 N at 20 mm/s, then loaded to failure at 20 mm/s	PDS2-0	FL, E, FM
Nguyen et al. (2020) [54]	16	59-81	50%	Krackow, MFSS cable crimp	Loaded for 100 cycles from 10 to 50 N, then loaded to failure at 25 mm/s	Fw2,	FL, E, FM
Cottom et al. (2017) [12]	36	NR	NR	Krackow, PARS, PARS/ Midsubstance	Loaded for 1000 cycles from 20 to 100 N, then loaded to failure at 25.4 m/s	Fw2, SwL	FL, E, FM
Van Dyke et al. (2017) [75]	24	74.3	NR	"Giftbox" Krackow, Bunnell	Loaded for 1000 cycles from 20 to 100 N, then loaded to failure at 0.2 mm/s	Fw2	FL, E, FM
Clanton et al. (2015) [10]	33	53 (25-65)	57.6%	Triple Kessler, Achillon, PARS, PARS/ Midsubstance	Loaded for 250 cycles from 20 to 100 N at 1 Hz	Fw2, SwL	E, FM
Demetracopoulos et al. (2014) [14]	31	54.8 ± 11.9	NR	Achillon, PARS	Loaded to failure at 25 mm/s	Fw2	FL, FM
Heitman et al. (2011) [23]	19	75.3 ± 10	NR	Krackow, Achillon	Loaded to failure at 25.4 mm/s	Eth1	FL, FM
McCoy et al. (2010) [50]	24	NR	NR	Double Bunnell, double Krackow, double Kessler	Loaded to failure at 85 mm/s	Mrs2	FL, FM
Herbort et al. (2008) [24]	24	61.9 ± 11.7	66.7%	Bunnell, Kessler	Loaded for 1000 cycles from 5 to 20 N at 20 mm/min	PDS5	FL, E, FM
Huffard et al. (2008) [28]	20	33.4 ± 4.9	NR	Achillon, double Krackow	Loaded to failure at 25 mm/s	Eth1	FL, FM
Jaakkola et al. (2000) [30]	16	NR (62-82)	NR	Triple Bundle, double Krackow	Loaded to failure at 2.54 mm/s	Eth1	FL, FM

Continuation of table 18

STUDY	N	AGE	% MALES	TECHNIQUES	LOADING PROTOCOL	MATERIALS	OUTCOMES
COMPARISONS WITH AUGMENTATION PROCEDURES USING BIOMATERIALS/AUTOGRAFTS							
Berlet et al. (2014) [6]	20	NR (25-55)	100%	Krackow with/without collagen ribbon augmentation	Loaded for 20 cycles at 2 to 30 N at 5 N/s, then laoded to failure at 6 mm/s	Eth2, TCR	FL, E, FM
Wisbeck et al. (2012) [77]	12	79.3 (69-88)	66.7%	Krackow with/ without porcine dermal matrix	Loaded to failure at 5 mm/s	FF2, Cnx	FL, FM
Magnussen et al. (2011) [46]	20	48 (21-64)	90%	Krackow with/ without bovine extracellular matrix augmentation	Loaded for 1000 cycles from 10 to 86 N at 0.5 Hz, then loaded to failure at 6 mm/s	FF2, TM	FL, E, FM
Barber et al. (2008) [5]	16	NR	NR	Krackow with/ without acellular allograft dermal matrix augmentation	Loaded for 20 cycles from 2 to 30 N at 5 N/s, then loaded to failure at 6 mm/s	Oc2, GrJ	FL, E, FM
Gebauer et al. (2007) [20]	40	44.9 (15-67)	74%	Bunnell, Kessler, with/without PT augmentation	Loaded to failure at 1.66 mm/s	PDS1, PDS5, PT	FL, FM

Cnx: Conexa; DLKS: double loop knot stitch; Eth1: No. 1 Ethibond; Eth2: No. 2 Ethibond Excel; FF2: No. 2 Force Fiber; FL: failure load; FM: description of failure mechanisms; Fw2: No. 2 FiberWire; E: measurement of elongation after cyclic loading; GrJ: GraftJacket; MFSS: multifilament stainless steel; Mrs2: No. 2 Mersilene; N: total number of specimens; NR: not reported; Oc2: No. 2 Orthcord; PDS1: No. 1 PDS; PDS2-0: 2-0 PDS; PDS5: No. 5 PDS; PT: Plantaris tendon; SwL: SwiveLock suture anchor; TCR: Trellis Collagen Ribbon; TM: TissueMend Soft Tissue Repair Matrix.
All values represented as means and standard deviations, except where stated otherwise.

All studies described the method used to simulate an ATR, with transection using a conventional scalpel being used across all studies. This transverse cut was performed at a distance from the calcaneal insertion of 2- [24], 3- [54], 4- [5, 12, 14, 23, 30, 46, 75, 77], 4.5- [18, 28], 5- [6, 20, 50] and 6 cm [10].

Ten out of the sixteen studies reported conflicts of interest or relevant financial disclosures [5, 6, 10, 14, 20, 23, 46, 54, 75, 77], four studies reported no conflicts of interest or financial disclosures [12, 18, 28, 50], and in the remaining two studies this information was not provided [24, 30].

Fifteen studies included failure load as an outcome [5, 6, 10, 14, 18, 20, 23, 24, 28, 30, 46, 50, 54, 75, 77]. Failure load was defined as load that induced gapping equal to or higher than 5 mm in three studies [10, 75, 77]. Nine studies included elongation with cyclic loading as an outcome [5, 6, 10, 12, 18, 24, 46, 54, 75]. Three studies measured total construct elongation [5, 10, 24], four studies measured gapping between tendon ends [6, 18, 54, 75], and two studies used other references [12, 46]. Mean values and standard deviations pertaining to each technique and study, per outcome, can be seen in Figures 33 and 34.

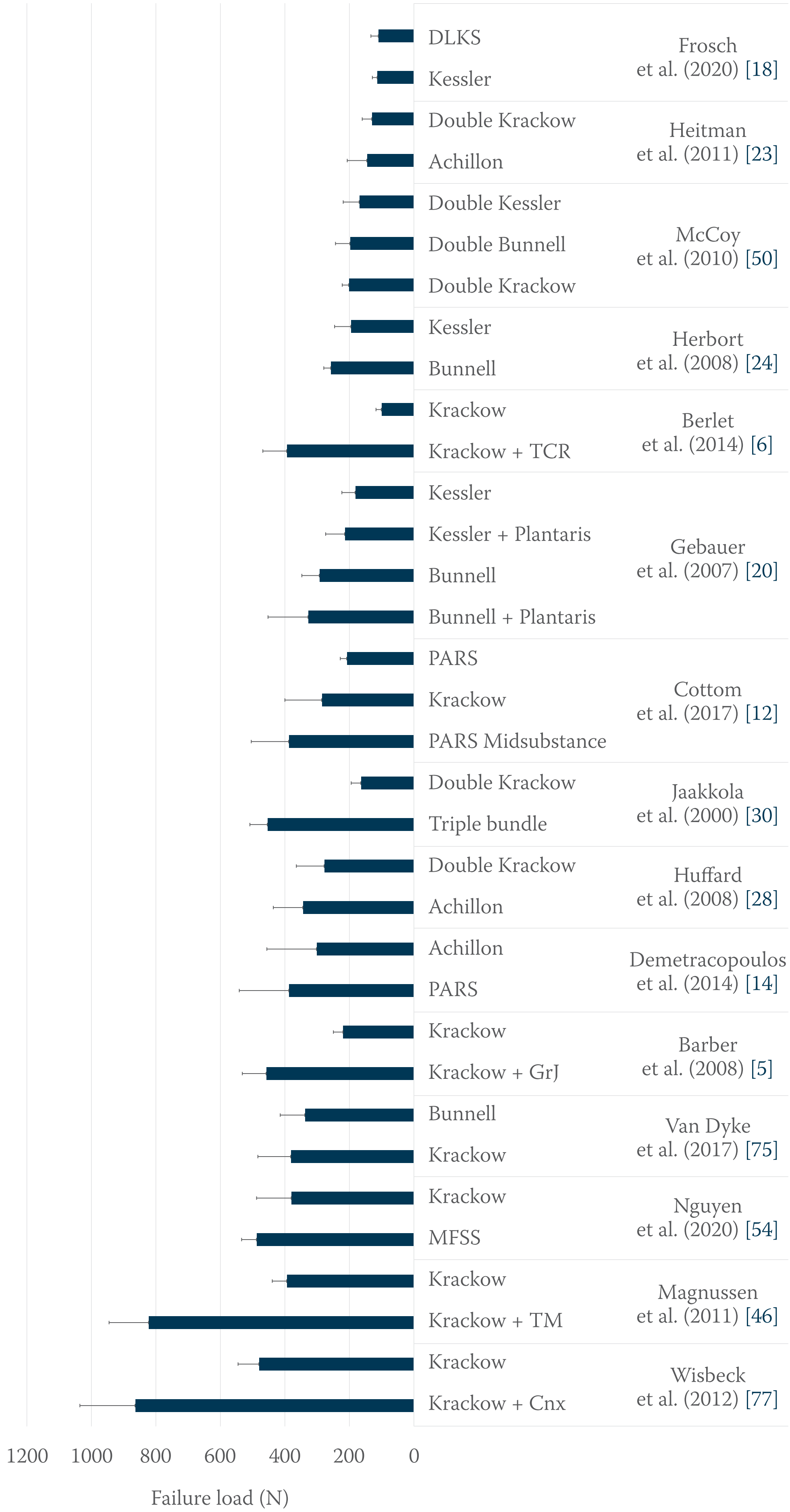
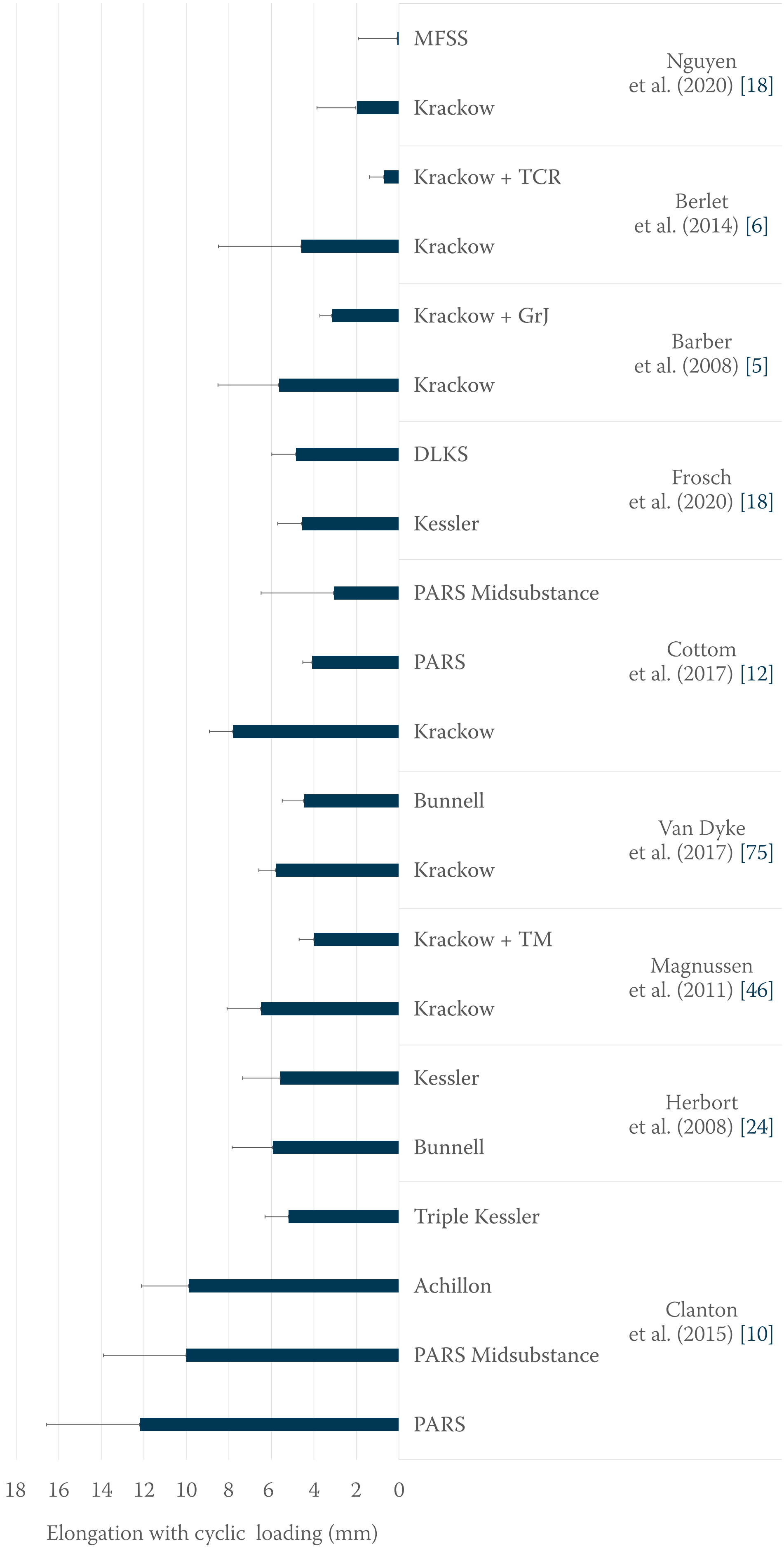


FIGURE 33 | Mean and standard deviation of reported values of included techniques in failure load meta-analysis (Newtons). DLKS: double loop knot stitch; Kessler or Bunnell + Plantaris: augmentation of the repair with a plantaris tendon. Krackow + [biomaterial]: techniques in which the Krackow repair was augmented with a biomaterial; Cnx: Conexa; GrJ: GraftJacket; TCR: Trellis Collagen Ribbon; TM: TissueMend Soft Tissue Repair Matrix. MFSS: multifilament stainless steel. PARS: Percutaneous Achilles Repair System; PARS Midsubstance: augmentation of the PARS technique with suture anchors.

FIGURE 34 | Mean and standard deviation of reported values of included techniques in elongation with cyclic loading meta-analysis (mm). DLKS: double loop knot stitch; Krackow + [biomaterial]: techniques in which the Krackow repair was augmented with a biomaterial; GrJ: GraftJacket; TCR: Trellis Collagen Ribbon; TM: TissueMend Soft Tissue Repair Matrix. MFSS: multifilament stainless steel. PARS: Percutaneous Achilles Repair System; PARS Midsubstance: augmentation of the PARS technique with suture anchors.



Risk of bias in individual studies

A summary of risk of bias in individual studies is shown in Figure 35. A table detailing risk of bias in individual studies can be found in Appendix II (Table II-B).

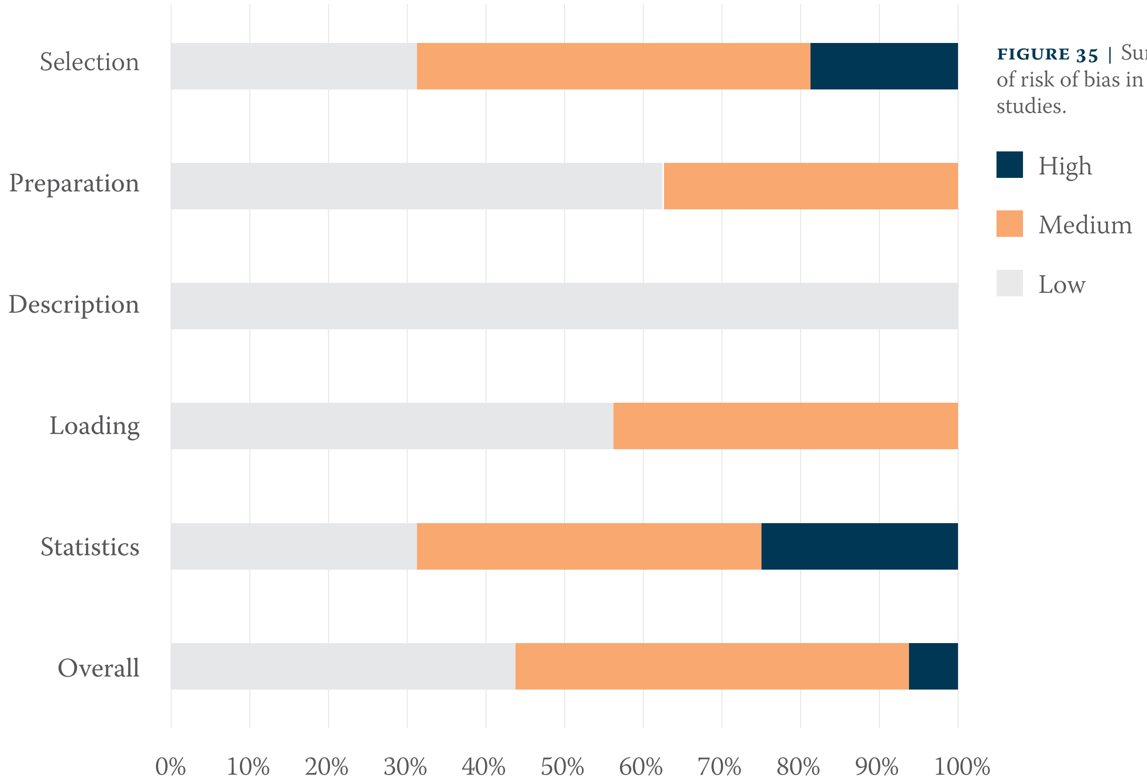


FIGURE 35 | Summary of risk of bias in included studies.

Primary outcomes

The graphical representation of both networks can be seen in Figure 36. League tables showing all pairwise comparisons for both NMAs can be seen in Tables II-C and II-D (Appendix II).

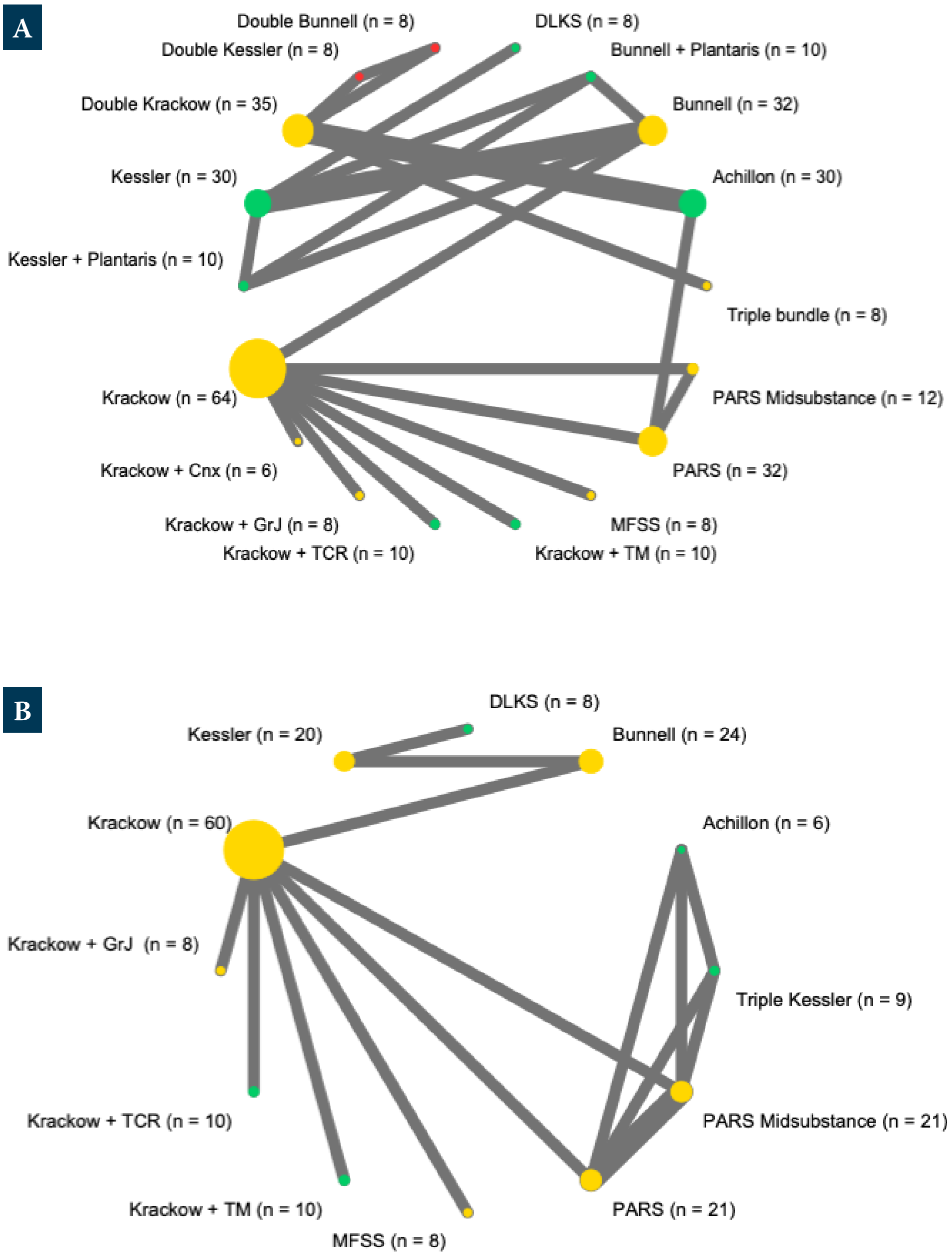


FIGURE 36 | Network geometries of included techniques in failure load meta-analysis (A) and elongation with cyclic loading meta-analysis (B). Surgical techniques are represented by circles and direct comparisons between techniques by lines between circles. The thickness of the lines represents the total number of studies in that comparison. The size of the circles represents the relative quantity of included specimens making use of that surgical technique (n = number of specimens). Average risk of bias (from the overall risk of bias in each individual study) for each technique is represented by the color of the node: green is low risk, yellow is moderate risk and red is high risk of bias. DLKS: double loop knot stitch; Krackow + [biomaterial]: techniques in which the Krackow repair was augmented with a biomaterial; GrJ: GraftJacket; TCR: Trellis Collagen Ribbon; TM: TissueMend Soft Tissue Repair Matrix. MFSS: multifilament stainless steel. PARS: Percutaneous Achilles Repair System; PARS Midsubstance: augmentation of the PARS technique with suture anchors.

For the failure load NMA, clinically important size of effect was set at 34.5 N. The estimated value of between-study (Tau^2) variance for this NMA was 686. The I^2 value was 55.7% (0.0-87.4%) and the Cochran's Q equivalent total was 4.5 (p = 0.11, 2 degrees of freedom).

For the elongation after cyclic loading NMA, clinically important size of effect was set at 0.9 mm. The estimated value of between-study (Tau^2) variance for this NMA was 0. The I^2 value was 0% and the Cochran's Q equivalent total was 0.3 ($p = 0.59$, 1 degree of freedom).

The ranking of the surgical techniques, according to the P-score, can be found in Tables 19 and 20. Forest plots of results for both networks can be found in Appendix II (Figures II-A and II-B). The Spearman's Rank correlation coefficient (r_s) was 0.11 (n.s.), meaning that a negligible correlation between rankings was found.

TABLE 19 | P-SCORE RANKING FOR FAILURE LOAD NETWORK META-ANALYSIS

		P-SCORE
1	Krackow + TM	0.981
2	Krackow + Cnx	0.947
3	Krackow + TCR	0.882
4	Krackow + GrJ	0.828
5	MFSS	0.702
6	PARS Midsubstance	0.695
7	Triple bundle	0.680
8	Bunnell + Plantaris	0.562
9	Krackow	0.548
10	Bunnell	0.463
11	PARS	0.380
12	Kessler + Plantaris	0.297
13	Kessler	0.240
14	DLKS	0.233
15	Achillon	0.228
16	Double Krackow	0.140
17	Double Bunnell	0.136
18	Double Kessler	0.059

Ranking of techniques in the failure load network meta-analysis, using the *netrank* function in *netmeta* [61]. A higher P-score represents the likelihood of a given technique ranking first in comparison with other techniques [62]. Kessler or Bunnell + Plantaris: augmentation of the repair with a plantaris tendon. Krackow + [biomaterial]: techniques in which the Krackow repair was augmented with a biomaterial; Cnx: Conexa; GrJ: GraftJacket; TCR: Trellis Collagen Ribbon; TM: TissueMend Soft Tissue Repair Matrix. DLKS: double loop knot stitch; MFSS: multifilament stainless steel. PARS: Percutaneous Achilles Repair System; PARS Midsubstance: augmentation of the PARS technique with suture anchors.

TABLE 20 | P-SCORE RANKING FOR ELONGATION WITH CYCLIC LOADING NETWORK META-ANALYSIS

		P-SCORE
1	Triple Kessler	1.000
2	Achillon	0.838
3	PARS Midsubstance	0.814
4	Krackow + TCR	0.673
5	PARS	0.672
6	Krackow + TM	0.455
7	Krackow + GrJ	0.448
8	MFSS	0.343
9	Kessler	0.305
10	DLKS	0.237
11	Bunnell	0.202
12	Krackow	0.012

Ranking of techniques in the elongation with cyclic loading network meta-analysis, using the *netrank* function in *netmeta* [61]. A higher P-score represents the likelihood of a given technique ranking first in comparison with other techniques [62]. Krackow + [biomaterial]: techniques in which the Krackow repair was augmented with a biomaterial; GrJ: GraftJacket; TCR: Trellis Collagen Ribbon; TM: TissueMend Soft Tissue Repair Matrix. DLKS: double loop knot stitch. MFSS: multifilament stainless steel. PARS: Percutaneous Achilles Repair System; PARS Midsubstance: augmentation of the PARS technique with suture anchors.

Results of sensitivity analysis

Six studies used specimens from elderly cadavers [18, 23, 30, 54, 75, 77]. Five studies did not use matched pairs in their comparisons [10, 12, 14, 20, 50]. Subgroup sensitivity analysis did not change the ranking of the techniques within the remaining studies, except in the elongation after cyclic loading NMA with exclusion of studies with specimens from elderly patients. In this NMA, the Krackow stitch augmented with TissueMend Soft Tissue Repair Matrix and the Krackow stitch augmented GraftJacket switched positions; the remaining techniques kept their rankings. Results can be found in Appendix II (Table II-E).

Separating the “Giftbox” Krackow with epitendinous weave into a different node had no influence on the P-score rankings within resulting subnetworks (Appendix II, Table II-F). After separating techniques with epitendinous weave augmentations into different nodes, one of the aforementioned studies [75] (containing “Giftbox” Krackow and Bunnell repairs with epitendinous weave augmentations) became isolated and was excluded. The two other techniques [10, 54] pertain to single studies and were already placed in their own nodes, thus, further network reorganization was unwarranted. No influence in P-score rankings was observed.

The exclusion of studies making comparisons with augmentation procedures using biomaterials/autografts had a noticeable effect on statistical heterogeneity in the failure load NMA. Tau^2 variance was reduced from 686.01 to 292.69 and the I^2 value from 55.7% to 21%. The Cochran's Q equivalent total was 1.3 (n.s.; 1 degree of freedom) *versus* 4.5 (n.s., 2 degrees of freedom) in the previous analysis. The exclusion of these studies had no effect on the rankings of the remaining techniques in both NMAs.

Results of assessment of confidence in findings

The detailed report for both analyses can be seen in Appendix II (Tables II-G and H). Reporting bias, a feature of risk of bias across studies, was considered unsuspected for all comparisons. For failure load, confidence in the results of the NMA was rated as low-to-moderate. For the elongation after cyclic loading, confidence in the results of the NMA was rated as moderate.

Secondary outcome

All studies reported failure mechanisms. Failure mechanisms were reported for 360 of 367 specimens. Most failures occurred by suture or scaffold breakage (56.4%, compared with 29.4% by disruption of the suture-tendon interface). Other modes of failure accounted for 14.2%. Data related to this outcome can be found in the Appendix II (Table II-I).

A negligible inverse correlation between percentage of failures due to disruption of the suture-tendon interface and P-score in the failure load NMA ($r = -0.15$; 95% confidence interval: -0.58 to 0.34; n.s.) and a moderate correlation with P-score in the elongation with cyclic loading NMA ($r = 0.67$; 95% confidence interval: 0.18 to 0.90; $p = 0.02$) were found. A moderate correlation between percentage of failures due to suture or scaffold failure and P-score in the failure load NMA ($r = 0.45$; 95% confidence interval: -0.02 to 0.76; n.s.) and a negligible inverse correlation with P-score in the elongation with cyclic loading NMA ($r = -0.15$; 95% confidence interval: -0.67 to 0.46; n.s.) were found.

DISCUSSION

This study's primary aim was to systematically review the literature regarding *in-vitro* testing of AT repair techniques in human cadavers, rank these according to failure load and elongation after cyclic loading and evaluate if rankings were statistically correlated. The secondary aim was to investigate failure mechanisms and statistical correlations between these and rankings of techniques.

Krackow stitches augmented with biomaterials ranked highest in the failure load NMA [5, 6, 46, 77]. The increased tensile strength of these repairs may be related to load sharing between biomaterial and core repair construct, as hypothesized by Berlet et al [6]. Next in the ranking were the MFSS [54], PARS Midsubstance [12] and triple bundle stitch [30]. These techniques ranked higher than the Krackow stitch, which is still considered the gold standard for soft tissue fixation [68]. Their superiority may be related to the number of suture strands crossing the rupture site [73], avoiding the use of knots, or tying of sutures away from the rupture site [30]. Interestingly, the double Krackow ranked lower than the single Krackow stitch, which may be attributed to differences in suture materials: all double Krackow repairs used braided polyester sutures, while Krackow repairs were performed using polyblend polyethylene sutures in seven of eight studies [5, 6, 12, 46, 54, 75, 77]. Suture *in-vitro* studies have shown the superiority of polyblend polyethylene compared with braided polyester [4, 11, 79], with the former displaying a 2- to 2.5-fold increase in tensile strength [11, 79].

The modified triple Kessler [10] stitch ranked first in the elongation after cyclic loading NMA. This technique was reinforced with an epitendinous weave [10], which has been previously shown to increase resistance to gapping in a single loading test [40] and may have contributed to its superior outcome. Of note, two studies found that a significant percentage of elongation occurred in the first ten cycles [10, 46]. Cycling the repair construct before knot tying or anchor fixation may be considered to lessen the risk of tendon elongation.

A negligible correlation between rankings in both NMAs was found ($r_s = 0.11$), meaning that evidence of superior performance in failure load testing being related to less elongation with cyclic loading was not found. A moderate correlation between the P-score in the elongation with cyclic loading and the percentage of failures occurring by suture pull-out was found ($r = -0.67$), but the wide-ranging 95% confidence interval (0.18 to 0.90) precludes any definite assumptions, despite statistical significance ($p = 0.02$).

This topic was the subject of previous systematic reviews by Sadoghi et al. [63] and Yammine et al. [80]. Sadoghi et al. published a systematic review without meta-analysis [63]. Eleven studies were included, comprising 196 specimens, but the authors refrained from performing a quantitative synthesis due to concerns regarding small sample sizes, study designs and heterogeneity. Yammine et al. performed a systematic review and meta-analysis, in which a pairwise quantitative synthesis of tensile strength testing was done with eleven studies. These authors concluded that the Achillon, Bunnell and Krackow techniques had equivalent load-to-failure and that Bunnell and Krackow were stronger than Kessler repairs. However, substantial heterogeneity ($I^2 > 75\%$) was found for all pairwise comparisons except for Bunnell versus Kessler ($I^2 = 63\%$). These findings are in partial agreement with this NMA. While Bunnell and Krackow stitches were also favored in pairwise comparisons with the Kessler stitch, mean differences in pairwise comparisons between the Achillon, Bunnell and Krackow stitches favored the latter. Although evaluating the same outcome, the present study provides new information since a total of eighteen techniques were analyzed, several additional pairwise comparisons were made, and a ranking of techniques was constructed.

The main limitations of this systematic review and NMA are related to the small number of included studies and statistical and methodological heterogeneity.

For some techniques (double Kessler [50], modified triple Kessler [10], triple bundle stitch [30] and MFSS cable-crimp technique [54]), only one study was available. Accordingly, the risk of bias in individual studies was carefully evaluated and is reflected in the assessment of confidence in findings.

A concern might arise where, due to publication bias, studies reporting improved outcomes of new techniques, compared with the Krackow stitch, would be published, whereas studies failing to show improvements would not. The larger number of specimens repaired with Krackow stitches, comparing unfavorably with other techniques, could lower this technique's ranking. However, evidence of publication bias was not found. Also, supporting the validity of results, incoherence in the networks was not present, although the number of strict indirect comparisons was limited due to the low number of studies available.

Concerns related to statistical heterogeneity were mainly found in the failure load NMA. These might be due to discrepancies within techniques, asymmetries regarding suture materials and differences in loading protocols and measurements. Sensitivity analysis revealed that a significant portion of statistical heterogeneity was due to the inclusion of studies reporting comparisons with augmentation procedures with biomaterials/autografts. Despite extremely low statistical heterogeneity in the elongation with cyclic loading NMA, results still need to be cautiously interpreted since very low values of I^2 may be biased in small and sparse networks [27].

The number of cycles varied widely in the elongation with cyclic loading NMA (20 to 1000), but this may be thought to not significantly influence outcomes since most elongation seemingly occurs in the first ten cycles [10, 46]. Furthermore, higher ranking techniques were not featured within studies with a small number of loading cycles [5, 6].

Some studies included specimens from cadavers of elderly patients, which might constitute another limitation of this review. While subgroup analysis showed that excluding these studies did not change the results, it should be noted that studies not reporting specimen ages had to be included to perform an NMA.

Finally, another limitation of this review is the lack of a validated quality evaluation tool. There is currently no validated tool for risk of bias assessment of biomechanical *in-vitro* studies to the authors' knowledge. However, the tool used herein was developed purposely for this review and is highly specific to this study's objective.

Future studies may perform additional comparisons between techniques, or modifications, regarding tensile strength and elongation with cyclic loading. The role of suture materials on outcomes also warrants further investigation.

Finally, developing a validated risk of bias assessment tool for qualitative evaluation of biomechanical *in-vitro* studies may be of interest. Such a tool could contribute to the standardization of research methods in this area.

Implications for clinical practice

Current treatment recommendations emphasize preservation of tendon length and physiologic tension [33]. In this study, a modified triple Kessler augmented with an epitendinous weave was shown to be superior to other techniques regarding resistance to elongation with cyclic loading in a cadaveric model.

Some surgeons, however, may want to avoid open techniques due to concerns over wound healing complications [7, 78] or for cosmetic reasons. In their systematic review and NMA, Wu et al. reported that a minimally invasive surgical treatment might be a preferable choice due to a lower global incidence of major complications than other treatment options [78]. Considering this perspective, the PARS Midsubstance technique may also be deemed a sensible option since it ranked relatively high in both NMAs.

Surgeons should consider, however, that tendon lengthening has been found to occur outside the rupture site as well [66] and that other aspects, such as rehabilitation program demands and suture material properties, should be taken into account [48]. Furthermore, knee extension with the ankle immobilized at 0 degrees imposes loads on the AT averaging 86.5 N [13], which exceeds the maximum applied load in some of the included studies. Thus, noticeable tendon elongation can occur even at relatively low loads. Current rehabilitation protocols emphasize early weight-bearing and mobilization, which may exceed the loading capacity of existing surgical repair techniques and materials.

CONCLUSION

The present NMAs of human cadaveric studies showed that the modified triple Kessler stitch displayed the highest probability of ranking first regarding resistance to elongation with cyclic loading, followed by the Achillon and PARS Midsubstance techniques. Noticeable statistical heterogeneity was found in the failure load NMA, in which biomaterial augmented Krackow repairs ranked highest, followed by the MFSS and PARS Midsubstance techniques.

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Section Delta

A novel treatment approach to Achilles tendon ruptures

Chapter 8: Endoscopic Flexor Hallucis Longus Transfer for the Management of Acute Achilles Tendon Ruptures: A Prospective Case Series Report With a Minimum of 18 Months' Follow-Up

Chapter 9: Early analysis shows that endoscopic flexor hallucis longus transfer has a promising cost-effectiveness profile in the treatment of acute Achilles tendon ruptures

CHAPTER 8

Endoscopic Flexor Hallucis Longus Transfer for the Management of Acute Achilles Tendon Ruptures: A Prospective Case Series Report With a Minimum of 18 Months' Follow-Up

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This chapter features a case series from the two first authors of this study.

INTRODUCTION

Acute Achilles tendon rupture (AATR) is a frequent injury occurring predominantly in young to middle-aged males. The goal of treatment is to restore Achilles tendon function to as close as possible to its preinjury state, with minimal complications, and providing early mobilization if these repair techniques render this possible [23, 27, 29, 36, 53, 54, 62, 73].

AATR can be treated with either surgical or nonsurgical options. With conservative treatment, a period of immobilization, usually ranging from 6 to 8 weeks, using a splint, closed cast, or walker boot has been proposed. Several different nonoperative protocols exist: immobilizing with the foot in plantarflexion position from the start or with the foot initially placed in plantarflexion (at different degrees) and progressing to neutral position, with or without "early" physiotherapy and "functional" rehabilitation [4, 30, 39, 67]. Surgical management options usually include open, percutaneous, or minimally invasive repair of the tendon [1, 9, 15, 24, 35, 38, 40, 42]. However, the optimal treatment method has not yet been definitively established and remains somewhat controversial [13, 20, 35, 71, 73].

Based on the best available evidence, minimally invasive surgical approach methods may provide some advantages compared with open surgery for treating AATR. These include keeping the tendon healing in a "closed environment," lesser dissection to the traumatized tendon, potentially reducing the incidence of neurovascular complications, minimizing skin healing issues (including noncosmetic scarring), and the possibility of a lower infection rate [28]. However, because of limitations of the available studies, several authors recommended caution when considering such statements, and further high-quality studies are needed before assuming more definitive conclusions [37, 40, 65]. Associated systemic diseases, age, and general health of the patient may influence the decision between these alternatives [53, 54, 67]. Moreover, several open repair techniques of AATR have also been used with favorable results [1, 23, 29, 42]. It has been stated that this approach offers adequate mechanical stability by providing better gap resistance and greater ultimate tensile strength, thus possibly enabling more "aggressive" rehabilitation protocols [41].

The flexor hallucis longus (FHL) or the peroneus brevis transfer have both been used to augment the Achilles tendon (AT) in patients with Achilles tendinosis and large chronic defects, either isolated or combined with other procedures [8, 25, 46, 47, 51, 68, 70]. However, to the best of our knowledge, only a single case report describing the use of isolated endoscopic FHL transfer to treat acute Achilles tendon ruptures has been reported [43]. In that case report, the technique used was minimally invasive and the FHL was harvested distally and rerouted to the ruptured proximal portion of the tendon and then passed transosseously through the calcaneus. A favorable outcome was reported, and to the best of our knowledge, there have been no similar reports in the literature; consequently, further studies are needed.

The aim of this study was to describe the clinical outcomes of isolated endoscopic FHL transfer in a case series of patients with acute Achilles tendon ruptures and a minimum follow-up period of 18 months. The study hypothesis was that this surgical approach is at least as effective (based on clinical and functional assessment at short- and intermediate-term follow-up) as the classic conservative or surgical treatment options reported in the literature.

PATIENTS AND METHODS

Institutional review board approval was obtained, and all patients signed the specific informed consent. Patients were enrolled prospectively and consecutively and underwent the procedure between December 2015 and January 2018. Participation in the study was offered to all patients for whom operative repair of the Achilles tendon was indicated. All included patients were offered a choice between the “traditional” methods of repair and the current technique. A detailed explanation of the expected advantages and disadvantages was given to each patient, after which informed consent was agreed on by the patients. Fifty-six male patients (mean age ± standard deviation, 36.39 ± 8.1 years) who underwent endoscopic FHL transfer as management for acute Achilles tendon ruptures were ultimately included. Forty patients (71.4%) were involved in sporting activity on a professional or regular recreational basis (more than twice a week). Patients with previous surgeries or insertional or noninsertional Achilles tendinopathy were excluded.

Preoperative magnetic resonance imaging (MRI) was performed in all patients, and Chan’s classification [12] was used to classify the Achilles tendon rupture level: 51 free tendon (21 proximal, 18 middle, and 12 distal) and 5 insertional cases were included. No systemic risk factors were identified in 38 of 56 patients. In the remaining 18 patients (32.1%), certain risk factors were detected: smoking, hypercholesterolemia, use of statins, arterial hypertension, or high body mass index. Patient demographics are shown in Table 21.

TABLE 21 | PATIENT DEMOGRAPHICS

SIDE	
Right	24 (42.9)
Left	32 (57.1)
Risk Factors	
None	38 (67.9)
Anticholesterol drugs	9 (16.1)
Hypertension	3 (5.4)
Overweight	2 (3.6)
ACHILLES TENDON RUPTURE SITE (CHAN CLASSIFICATION)	
Insertional	5 (8.9)
Proximal	21 (37.5)
Middle	18 (32.1)
Distal	12 (21.4)
AGE (Y)	
Mean ± SD	36.39 ± 8.11
Median (range)	35.50 (25.00 to 59.00)
FOLLOW-UP (MO)	
Mean ± SD	27.53 ± 7.29
Median (range)	27.00 (18.00 to 43.00)

Patient demographics (N = 56). Data are n (%) unless noted otherwise.

The study protocol included clinical assessment with the Achilles tendon total rupture score (ATRS), American Orthopaedic Foot and Ankle Society (AOFAS) score, and visual analogue score (VAS) at a minimum of 18 months for all patients. Patients were also followed up at the last postoperative visit at a mean of 27.5 ± 7.29 months (range 18 to 43) after surgery. MRI was performed preoperatively, at 1 week (to document the tunnel position and provide a baseline for subsequent MRI follow-up studies), and 18 months after surgery. Hallux dynamometry for great toe flexion and ankle plantarflexion was assessed with the MicroFET2 isokinetic digital dynamometer (Hoggan Health Industries, West Jordan, UT). Assessment was made for the involved and the opposite sides at 18 months postoperatively to compare the strength of the hallux and ankle plantarflexion. Hallux plantarflexion strength was measured with the heel resting on the ground but with the knee flexed.

The patients were asked to maximally plantar flex the hallux only, and they were observed to ensure that the ankle remained in neutral, and that body weight was not shifted while recording the hallux plantarflexion strength. Ankle plantarflexion power was measured similarly, with the heel firmly on the ground and the patient seated with the knee extended. The patients were asked to maximally plantarflex the foot. Patients were observed closely to ensure that they did not use their body weight during measuring the plantarflexion strength. Strength was assessed by measuring peak force, the highest force value in kilograms. Each force measurement was assessed for 5 seconds, 5 times, and an average score was obtained for each measurement.

Achilles length was also measured using the Achilles tendon resting angle (ATRA) as has been previously described [7]. A standard goniometer, with 2 degree increments and 35-cm arm length (Medi, Bayrueth, Germany) was used. This measurement was used as a clinical and easily performed guide to tendon length during intra-operative repair and during the follow-up assessment of patients [74].

The primary outcome measure was the clinical assessment of the involved patients by the ATRS and AOFAS scores. Secondary outcome measures were the effect of this procedure on hallux and ankle plantarflexion power and on Achilles tendon lengthening clinically by easily reproducible methods.

Statistical analysis

Statistical data were coded and entered using the statistical package for the Social Sciences (SPSS) version 25 (IBM Corp., Armonk, NY). Data were summarized using mean, standard deviation, median, minimum, and maximum in quantitative data and using frequency (count) and relative frequency (percentage) for categorical data. For comparison of paired measurements within each patient, the nonparametric Friedman test and Wilcoxon signed rank test were used [10]. In comparison between normal and operated sides, paired t tests (2-tailed p values) were used. p Values <0.05 were considered statistically significant.

Surgical technique

The procedure was carried out under epidural anesthesia, with the patient in a prone position through the 2 classic posteromedial and posterolateral portals described by van Dijk et al. [16] (Figure 37). A pneumatic tourniquet was applied proximal to the knee. The ankle was placed over the distal edge of the operating table with a 5-cm silicone support underneath the distal part of the leg.

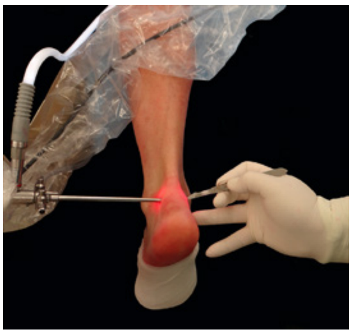


FIGURE 37 | Intraoperative photograph showing the 2 classic posteromedial and posterolateral posterior ankle arthroscopy portals as described by Van Dijk (40).

A 4.5-mm 30-degree arthroscope, with normal saline irrigation by gravity, was introduced through the posterolateral portal, 2 mm lateral to the Achilles tendon. The posterolateral portal was used primarily as the visualization portal, and the posteromedial portal as the working portal.

The posteromedial portal was made just 2 mm medial to the Achilles tendon. In the horizontal plane, it was located at the same level as the posterolateral portal. With a #11 surgical blade to perform the skin incision, a mosquito clamp was introduced and directed toward the arthroscope shaft until the tip of the mosquito clamp could be visualized. The retro-Achilles fascia and the ligament of Rouviere and Canela were resected as high as possible [8, 16].

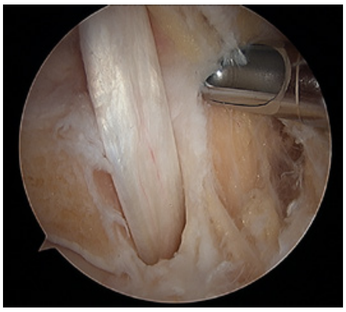


FIGURE 38 | Intraoperative release of the adhesions around the flexor hallucis longus (FHL) tendon.

The FHL tendon is an important landmark to prevent damage to the more medially located neurovascular structures. It is also our recommendation that no surgical work be performed medial to this structure [21]. Release of the FHL involves detachment of the flexor retinaculum from the posterior talar process. Adhesions surrounding the flexor tendon should be removed (Figure 38).

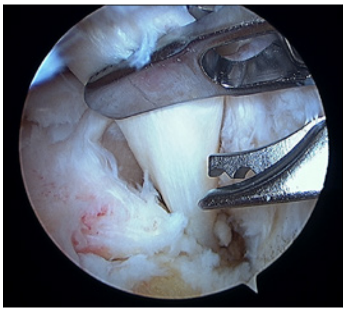


FIGURE 39 | An arthroscopic grasper was introduced through the posteromedial portal to grasp the flexor hallucis longus (FHL) tendon. This grasper was used to slide the FHL tendon medially and proximally. The grasped FHL tendon could then be transected with arthroscopic scissors.

The FHL tendon can be cut at zone 1 (behind the ankle joint) or zone 2 (from fibro-osseous tunnel posterior to talus to master knot of Henry) [45]. It is our preference to harvest the graft in zone 1 under direct posterior arthroscopic visualization just before its entrance into the fibro-osseous sheath.

FHL tendon length for transposition into the calcaneal bone should preferably not be less than 20 mm. The ankle and first metatarsophalangeal joint are fully plantarflexed, and through the posteromedial portal a grasper is introduced to pick up the FHL tendon, retract it, and slide it proximally to obtain the maximum tendon length [8] (Figure 39). The tendon is then cut with arthroscopic scissors introduced through the same portal while viewing continuously through the posterolateral portal.

With the harvested tendon withdrawn just outside of the arthroscopic posteromedial portal, a Krackow suture with No. 2 Ethibond is applied to the free end of the FHL distal tendon (Figure 40 A, B). An endoscopic calcaneoplasty is performed in all patients using a 5.0-mm resector shaver blade (Stryker, Kalamazoo, MI) to remove the posterosuperior edge of the calcaneal bone (Figure 41). This is an important step to allow positioning of the future calcaneal bony tunnel as far posterior as possible.

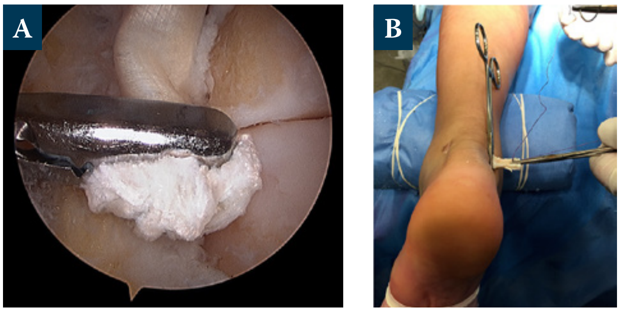


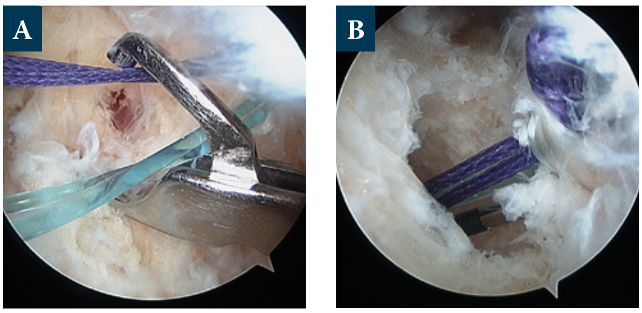
FIGURE 40 | (A) The free end of the flexor hallucis longus (FHL) tendon held with the grasper. (B) A Krackow suture was applied to the free distal end of the FHL tendon.

FIGURE 41 | Intraoperative photograph showing an endoscopic calcaneoplasty with resection of the posterosuperior edge of the calcaneal bone.

By palpation, immediately above the center of the posterior calcaneal tubercle, the third portal (central portal) is performed with a #11 knife. The calcaneal tunnel should be made through this portal with a 7-mm drill bit in a dorsal medial to plantar lateral direction under direct arthroscopic visualization.

The free end of the FHL tendon is then passed from the posteromedial portal to the central portal with a suture retriever device and then through the calcaneal bone tunnel in a plantar direction toward the plantar foot (Figure 42A, B). The FHL tendon is fixed with a 7-mm Biosure HA interference screw (Smith and Nephew, Andover, MA) (Figure 43A, B, C).

FIGURE 42 | (A) Intraoperative shuttling of the leading sutures of the flexor hallucis longus (FHL) distal tendon from the posteromedial portal to the central portal. (B) Passage of the leading sutures of the distal free end of the FHL tendon through the calcaneal bone tunnel in a plantar direction.



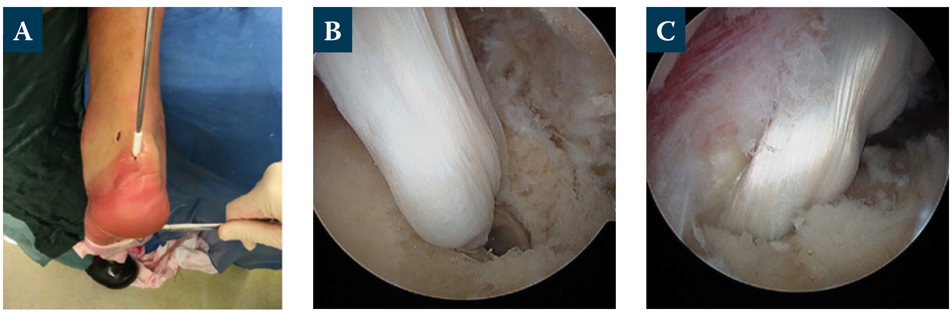


FIGURE 43 | (A) Intraoperative photograph showing the introduction of the screw over the guide wire from the central portal to the prepared calcaneal bone tunnel. (B) Intraoperative arthroscopic photograph showing the screw in place in the calcaneal bone tunnel. Note the far posterior placement of the tunnel and screw. (C) Assessment of the flexor hallucis longus (FHL) tendon in the calcaneal tunnel from either side of the tunnel.

During screw fixation, the FHL is introduced into the calcaneal tunnel, and the leading sutures are held in place mimicking the resting tension and length of the opposite normal side. We compare the operated and nonoperated limbs both immediately preoperatively and at that point during the operative procedure using the ATRA method [7]. Once the appropriate length and tension is found, this tension is held, and the screw is introduced and fixed in that position. For that reason, we surgically sterilize and drape the other uninjured normal side in all cases (Figure 44). The transferred tendon is visualized and palpated through both the posteromedial and posterolateral portals to ensure the proper fixation of the transfer (Figure 43B, C).

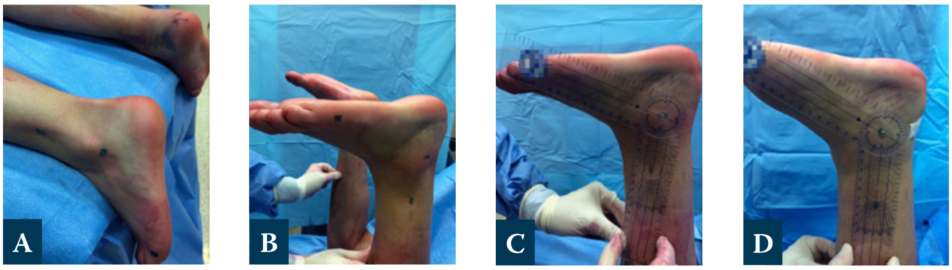


FIGURE 44 | (A) Intraoperative photograph: patient lying prone with both feet and legs prepared until above the knee to facilitate positioning for later Achilles tendon resting angle (ATRA) assessment and comparison. (B) Intraoperative photograph: comparison in resting tension between the 2 limbs. Note the relatively dorsiflexed position of the injured (right) limb. (C) Intraoperative assessment of the ATRA of the injured limb. (D) Immediate postoperative photograph: measurement of the ATRA of the operated limb with restoration of ATRA to as near as possible to the value of the contralateral side.

It has been suggested by some authors for chronic cases that this reconstruction be augmented by suturing the FHL tendon to the medial border of the distal stump of the Achilles tendon with no.2 Ethibond through the posteromedial portal [51]. This augmentation was not performed in the current series.

The wounds are closed with 3/0 Ethilon, and a neutral ankle short leg cast is applied. The cast is worn for 2 weeks. The patient is advised to be non-weightbearing for 1 week, and partial weightbearing is allowed during the second week. Patient is then moved to a walking boot and allowed full weightbearing between the third and fourth week. At that time, active mobilization of the ankle is allowed, with full range of motion in plantarflexion. After that, all patients start with a specific functional rehabilitation program along similar lines to Brumann et al. [21].

RESULTS

No patients were lost during the follow-up imaging, dynamometry measurements, or Achilles length evaluations. The mean follow-up duration was 27.5 ± 7.29 months (range 18 to 43). The FHL tendon was harvested at zone 1 in all patients. A prominent posterolateral process of the talus was resected in 2 cases before FHL tendon harvesting.

The harvested tendon diameter measured 5 mm in 32 patients, 5.5 mm in 14, and 6 mm in 10. The length of the tendon was enough to be transferred to the calcaneal tunnel without difficulty in all cases. The calcaneal tunnel was routinely drilled to 7 mm in diameter with a length of 30 mm. In our attempt to reproduce the resting tension of the contralateral uninjured side by using the ATRA measurement [74], it was found that ≥20 mm of transferred tendon was always in the tunnel in all of our included cases, and >30 mm of tendon was not needed in all operated cases. The calcaneal tunnel was placed at a mean of 2-mm distance (range 1 to 5 mm) from the most posterior aspect of the calcaneal bone. The FHL tendon was secured with a 7-mm-diameter (25- mm length) tendon anchor screw in all patients.

Postoperative MRI was carried out at a minimum of 18 months follow-up for all cases, and it showed a homogeneous continuous signal for 43 patients and heterogeneous signal intensity in 13 patients (23.21%) (Figures 45 and 46). Continuity and homogeneity of the Achilles tendon on the MRI images was documented and determined according to Goutallier et al. [22].

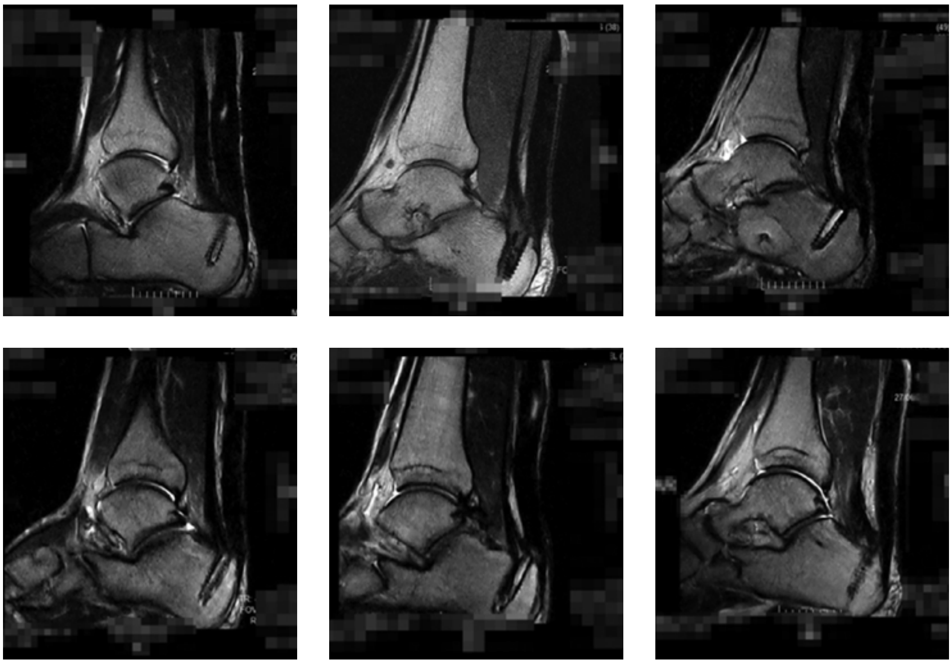


FIGURE 45 | Magnetic resonance imaging of several patients at 18 months postoperatively showing homogeneous signal of the Achilles tendon.

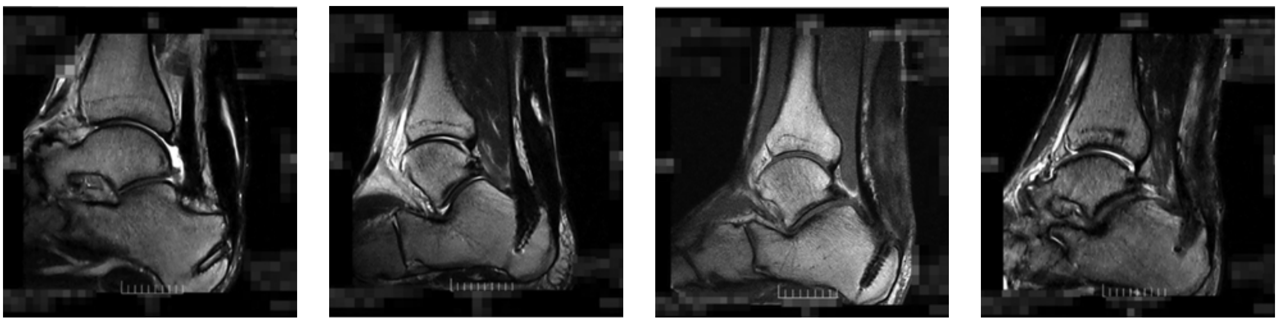


FIGURE 46 | Magnetic resonance imaging of several patients at 18 months postoperatively showing heterogeneous signal in the previously ruptured Achilles tendon.

Achilles tendon total rupture score (ATRS) was documented at 18 months for all patients. The mean was 95 ± 4.26 (range 80 to 100), and the AOFAS score at 18 months was a mean of 96 ± 4.86. Dynamometry testing was also performed at 18 months postoperatively. Regarding FHL tendon flexion power, the median value for the surgical side was 96.3 kg • m (range 70.1 to 143.8) and 93.7 kg • m (range 68-161) for the nonoperated side. Ankle plantarflexion power was also measured for all patients at 18 months postoperatively. Ankle plantarflexion power was recorded as a mean of 19.19 ± 2.55 kg • m compared with the nonoperative side of 19.27 ± 2.16 kg • m. ATRA was also documented and compared with the nonoperative side at 18 months postoperatively. The ATRA was recorded at a mean of 42.75° ± 8.09°. The relative ATRA was a mean of −0.25° ± 2.43°. The results of the current study are shown in Table 22.

TABLE 22 | RESULTS OBTAINED IN THE CURRENT STUDY

PARAMETER	MEAN	STANDARD DEVIATION	MEDIAN	MINIMUM	MAXIMUM	P VALUE
AOFAS, 18 mo	95.38	4.86	96.00	74.00	100.00	
ATRS, 18 mo	95.23	4.26	95.00	80.00	100.00	
VAS						
Preoperative	5.52	1.37	6.00	3.00	8.00	<.0001
18 mo	0.61	0.91	0.00	0.00	4.00	
FHL DYNAMOMETRY (KG • M), 18 MO						
Operated side	102.45	22.67	96.3	70.10	143.80	.2714
Contralateral side	103.46	23.05	93.7	68.00	161.00	
ANKLE PLANTARFLEXION STRENGTH (KG • M), 18 MO						
Operated side	19.19	2.55	18.90	14.2	24.90	.635
Contralateral side	19.27	2.16	19.45	15.3	23.5	
ATRA (°), 18 MO						
Operated side	42.75	8.09	44	24	58	.087
Contralateral side	43.32	8.25	44	26	56	
Relative ATRA (°), 18 mo	−0.25	2.43	−0.5	−6	6	

Results obtained in the current study (N = 56). Mo: months.

Minor complications (lasting less than a month postoperatively) were recorded in 6 patients (10.7%): portal pain in 4 patients and superficial infection in 2 patients. Major complications occurred in 4 patients (7.14%): deep venous thrombosis (DVT) and focal numbness occurred in 1 and 2 cases, respectively. A single case of Achilles tendon rerupture was reported. This occurred 2 months postoperatively when the patient sustained a slip on a wet surface during the postoperative rehabilitation. MRI documented that the retear occurred at the site of the previous Achilles tendon rupture. The transferred

FHL tendon was intact (Figure 47). This patient was immobilized in a walking boot for 3 weeks, then commenced with his preassigned physiotherapy regimen as usual. He returned to playing professional soccer uneventfully. His ATRS score was 85 at 18 months, but he scored 100 points at his final follow-up at 24 months postoperatively.

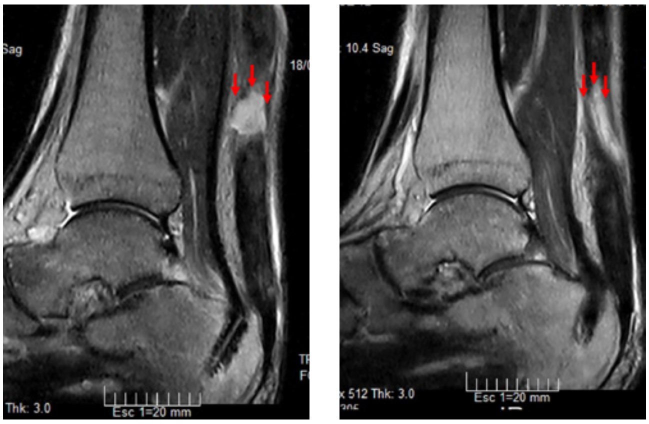


FIGURE 47 | Magnetic resonance imaging sagittal views of the patient that sustained rerupture of the Achilles tendon at the same site of previous rupture during his physiotherapy training, 2 months postoperatively. Note the intact transferred flexor hallucis longus (FHL) tendon. Patient was immobilized for 3 weeks and then continued in his physiotherapy protocol uneventfully.

At 18 months' follow-up, 20 and 16 patients recorded the maximum AOFAS score (100) and ATRS score, respectively. All patients (except the case of rerupture) returned to their daily activities without difficulties after 4 months. Return to previous preinjury levels of activity was reported by 44 of the 56 patients (78.5%). No patients reported any great toe complaints or symptomatic deficits of flexion strength as a consequence of the FHL tendon harvesting. No neurovascular or major skin complications were encountered.

DISCUSSION

The most important finding in the current study was that the results of this technique were comparable to other methods using surgical or functional conservative treatment methods in the management of acute Achilles tendon ruptures [4, 11, 15, 28, 29, 34, 36, 38, 56, 60, 73]. The current technique showed a 78.5% of return to preinjury activity, and this compared well with other similar studies [13, 15, 36, 40, 56, 73]. In a recent systematic and meta-analysis regarding return to sports, exclusively reviewing RCTs only, the examined studies had a combined ratio of 65.5% of patients in the surgical group of repairs [59]. This percentage was similar also in the previous study by Keating and Will [33], in which the authors showed a 70% return to sports (of 34 patients) in a functional prospective randomized evaluation of operative versus nonoperative treatments for AATR.

Most of the previous studies on AATR have used the AOFAS score as the outcome measure [6, 9, 13, 15, 33, 34, 40, 52, 56, 59, 60, 63, 71, 73]. Because comparisons were required to be made with these studies, the AOFAS score was also documented in this study. However, the Achilles tendon total rupture score (ATRS) was considered to be a more appropriate validated outcome measure for evaluating the management of AATR [55, 63]. We consequently present our results with both these outcome scores.

FHL tendon transfer has been used with success for chronic Achilles tendon problems with large defects [8, 24, 46, 47, 51, 70]. Endoscopic methods of FHL transfer have recently become more familiar [68]. Based on this, it seemed rational to use the same endoscopic technique for acute Achilles ruptures, especially considering that there is yet a consensus to be reached regarding the optimal method of management for AATR [13, 20, 71].

Although conservative treatment may provide a good option in the treatment of acute Achilles injuries, studies have shown a rerupture rate for cast immobilization ranging from 6.3% to 39% [23, 30]. Conservative functional treatment of these ruptures has shown better clinical results [3, 6, 38, 48]. Several meta-analyses have compared non-operative treatment to surgical treatment [28, 29, 56, 62, 71]. Similarly, rerupture rates were found to be higher in conservatively treated patients without functional rehabilitation [62]. Operative complications included superficial and deep wound infection, sural nerve dysfunction, wound healing issues, ankle stiffness, scar adhesion, fistulas, skin/tendon necrosis, tendon overlengthening, and pulmonary embolus [43, 44]. The results of these meta-analyses demonstrate that conservative treatment should be considered at centers using functional rehabilitation. This functional rehabilitation resulted in rerupture rates similar to those for surgical treatment while offering the advantage of a decrease in other complications. According to the authors, surgical repair should be preferred at centers that do not employ early range-of-motion protocols, which decrease the rerupture risk in such patients [62]. Recently, Ochen et al. [56] found similar results and further suggested that based on the systematic reviews they conducted, the final decision on the management of AATR should be based on patient-specific factors and shared decision making. All our patients were specifically informed with detailed explanations of the treatment options available and were actively involved in the choice of their respective management treatment protocols.

When comparing surgical with conservative methods, several authors found a low rerupture incidence with no significant differences between the 2 treatment groups in the incidence of DVT, return to sports, ankle range of motion (dorsiflexion, plantarflexion), Achilles tendon total rupture score, or physical activity scale. Consequently, surgical treatment may effectively reduce the rerupture rate and could be a better choice for the treatment of acute Achilles tendon rupture [8, 14, 49, 58]. According to other authors, percutaneous repair has the advantages of reduced operative time, reduced deep infection, and improvement of the AOFAS score. Despite the higher incidence of sural nerve injury, studies showed that percutaneous repair is superior to open repair for treating AATR [7, 11, 34].

Major complications secondary to surgical treatment of acute Achilles tendon rupture occur in ≤10% of cases and include deep infection, skin necrosis, tendon necrosis, and a draining sinus. The prevalence of minor complications is also substantial, with ≤15% of patients developing skin problems [62]. In a recent study published by Rozis et al [60], it was shown that superficial infection occurred in 7% and skin necrosis in 3% of cases undergoing open repair, and 6.9% developed paresthesia due to sural nerve entrapment in the percutaneous technique. In the current study, the recorded major and minor complications were similar to these numbers. The recorded minor complications resolved completely within 1 month, and major complications were documented in 7.1% of cases.

Numerous studies have demonstrated the benefit of FHL transfer for treating insertional and chronic AT ruptures [8, 19, 49, 64, 68–70]. Endoscopic methods of FHL transfer are recently gaining popularity [68], but to the best of our knowledge, this technique has not been described in relation to acute lesions. In 40 patients with chronic insertional Achilles tendinosis, Elias et al. [19] showed that operative repair using an FHL tendon with the single-incision technique achieved a high percentage of satisfactory results as well as excellent functional and clinical outcomes, including significant pain reduction. Recently, Vega et al [68] showed excellent results (AOFAS improved from 55 preoperatively to 91 preoperatively) in 22 patients who were endoscopically treated for chronic Achilles tendon rupture [68].

The advantages of FHL transfer include a long, thick, durable tendon with a stronger muscle than other tendon transfers [19, 67]; the axis of FHL contraction closely reproduces the Achilles tendon; and the FHL fires "in phase" with triceps surae during gait [14, 19, 69, 70]. The FHL tendon provides a distally located vascularized muscle belly and biomechanically strong tendon structure in close proximity to the injured Achilles tendon that might improve the vascularity to the affected tendon and thus possibly its healing process [19, 68–70]. Also, this anatomic proximity to the Achilles tendon allows easy harvesting of the FHL tendon, with less risk of damaging the neurovascular bundle [8, 64, 68].

Loss of push-off strength has been documented in several articles [17, 26, 50, 69, 70], and 1 study highlighted the significance of this loss in athletes [69]. When a double-incision technique was used and transection was made distal to the knot of Henry, difficulties were reported in harvesting the FHL tendon because of cross attachments between FHL and flexor digitorum longus, which required a more extensive dissection [31]. In the currently described technique, it was not necessary to obtain the FHL graft more distally at the level of the arch of the foot. The FHL tendon was transected endoscopically with arthroscopic scissors in zone 1 in all the patients. It is our opinion that if the tendon is harvested at the knot of Henry, a greater loss of hallux flexion power will occur than if the harvesting is performed in zone 1. It was of interest to note that, in the current study, the recorded ankle plantarflexion power was not significantly reduced compared with the uninjured side at 18 months postoperatively ($p = .634$).

Similarly, at the same point postoperatively, there was no documented significant loss of big toe flexion ($p = .2714$).

Carmont et al. [7] have shown that the ATRA may be used as a guide to measure Achilles tendon length during intraoperative repair and rehabilitation. They stated it was reliable, easily performed, cheap, and does not require radiation exposure or operator experience. In our technique, we did not perform tendon apposition of the Achilles rupture gaps. We relied on the dynamic and biological splintage provided by the transferred FHL and restoration of the Achilles length through the clinical intraoperative measurement of the ATRA. Also, just recently, Zellers et al. [74] demonstrated that the relative ATRA with knee flexed may be a better indicator of tendon elongation and also may be related to tendon mechanical properties and heel-rise test performance. We used this in evaluating our patients at 18 months postoperatively and found it also to be reliable and correlated with return to full function. In our results, the relative ATRA was a mean of −0.25° ± 2.43°, and the recorded angle for the operated side was not statistically significantly reduced compared with the uninjured side at 18 months postoperatively ($p = .087$)

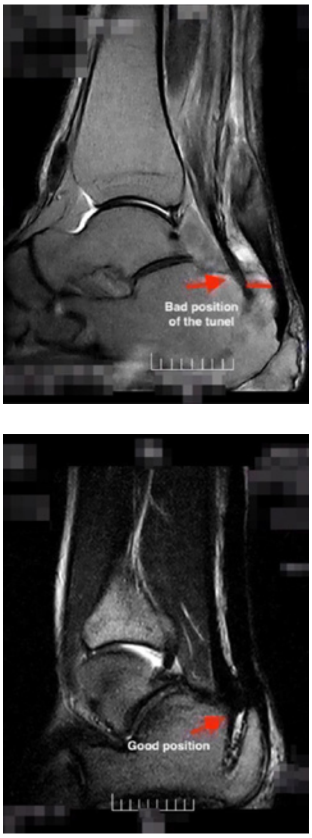


FIGURE 48 | Magnetic resonance imaging (MRI) showing bad position of the calcaneal tunnel with >1 cm anterior positioning from the posterior end of calcaneal bone (left), and good position of the calcaneal bone tunnel in the MRI of another patient with a far posterior positioning of the calcaneal tunnel (right).

Regarding the tunnel placement on the calcaneal bone, we have observed that the placement should be located as far posteriorly as is possible and as near as possible to the original Achilles tendon insertion site (Figure 48). This has also been documented by Arastu et al. [2]. To do this, an adequate resection of Kager's fat pad, of the retrocalcaneal bursa, and an endoscopic calcaneoplasty should be adequately performed. It is our hypothesis that in so doing, the muscle bulk of the transferred FHL is brought as close as possible to the torn Achilles tendon and will thus provide an adequate mechanical and biological vascular support for Achilles tendon healing. This will, in addition, allow arthroscopic visualization of the transferred FHL tendon in the tunnel and the exact position of the fixation screw and ensure that an adequate depth of the screw has been inserted into the calcaneal bone tunnel (Figure 43C). It has been shown that the transferred FHL muscle may show a mean hypertrophy of 52% [57]. This may also aid in biological healing of the tendon gaps, by providing vascular tissue in close proximity to a usually poorly vascularized part of the Achilles tendon.

Some studies showed no statistically significant difference between early and late weightbearing with conservative treatment, regarding the rerupture rate [61]. Other studies [18, 20] have also shown no statistically significant differences concerning the rerupture rate after early weightbearing in operative versus conservative treatment. Also, no differences were found in the occurrence of minor or major complications in both patient groups [20]. Previously, some authors have shown that maximum plantarflexion was not necessary to oppose tendon ends in acute Achilles tendon rupture [72]. More recently, other authors found that early dynamic functional rehabilitation is as safe, with a higher patient satisfaction, as immobilization after both surgical repair [52] and nonoperative management of AATR [32]. In the current case series, patients were placed in a neutral cast initially, then began to bear weight at the end of the first week. This was later followed by an accelerated rehabilitation protocol as cited by Brumann et al. [5]. We relied on the presence of the transferred FHL tendon acting as a dynamic biological and mechanical internal splint.

Regarding the MRI images, it was found that although 23.2% of patients (13 of 56) showed heterogeneous signals in their postoperative MRI scans, these patients showed very good or excellent results on the ATRS or AOFAS scores, in addition to ankle plantarflexion power comparable to their nonoperated sides. Consequently, the interpretation of heterogeneous signals or focal areas of nonconsolidation within the healing Achilles tendon on MRI scans should be made with caution and should not necessarily point to failures or reruptures, especially early after the initial surgery. Hypointense healed tendon tissue may take more than a year to become adequately apparent on MRI sequences. This finding was also recently reiterated by Tam and Lui [66].

The results at the end of this case series were encouraging. Patients were able to return back to their preinjury level in 78.5% of cases. A large number (71.4%) of the included patients in this current study were actively involved in sporting activity, whether on a professional or a regular recreational basis. In addition, possibly because of the dynamic FHL tendon transfer and secure fixation by an interference screw, the patients commenced their postoperative protocol from a neutral position of the ankle, and the period of immobilization and non-weightbearing was markedly reduced such that the included patients could commence with their rehabilitation protocol almost immediately.

A limitation of the present study is the lack of randomization and absence of a control group in the management of Achilles tendon ruptures. However, because a consensus is still lacking in the management of such injuries, this clinical trial was deemed appropriate as an attempt to reduce the rerupture rates and tendon elongations often associated with functional rehabilitation, while also reducing the complications linked with open or percutaneous management of acute Achilles tendon injuries. Also, the current study included males only, albeit naturally not by intention in a prospective study; however, it is still an obvious drawback. Also, the procedure might be technically demanding, especially for those surgeons not particularly familiar with posterior ankle arthroscopy, and thus might require a certain learning curve. Despite all of the above, and to the best of our knowledge, the current study is the first describing the endoscopic use of FHL transfer in the management of acute rupture of Achilles tendon and with a minimum follow-up of 18 months.

CONCLUSION

In conclusion, the current study demonstrates good comparable results with minimal complications using the FHL tendon for transfer in acute Achilles tendon ruptures. It can be a reproducible and effective procedure. No significant deficits were recorded in the flexor strength of the hallux, ankle plantarflexion, or Achilles tendon lengthening compared with the contralateral uninjured side. More studies with larger case series and follow-up, in addition to perhaps randomization of management methods, will be necessary to confirm these preliminary results.

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CHAPTER 9

Early analysis shows that endoscopic flexor hallucis longus transfer has a promising cost-effectiveness profile in the treatment of acute Achilles tendon ruptures

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INTRODUCTION

Achilles tendon ruptures (ATRs) are common injuries, with an incidence of 10.8 to 30.2 per 100.000 person-years [10]. Current options include conservative and surgical approaches. However, there is no consensus on whether early functional rehabilitation or surgical treatment (with a similar rehabilitation protocol) provides superior outcomes [50].

Long-term deficits are common regardless of adequate treatment [40]. Time-series analyses of isokinetic strength assessments in patients with ATRs revealed impairments in plantarflexor strength and a reduced capacity to sustain high levels of plantarflexor moment in the injured limb [57]. These strength deficits may be related to tendon elongation or inferior mechanical properties [16]. It is also noteworthy that Achilles tendon (AT) degenerative changes often, but not always, precedes rupture [49].

Flexor hallucis longus (FHL) hypertrophy is commonly observed after ATRs [25]. In addition, previous research has shown that soleus muscle atrophy is correlated with FHL and other deep flexors hypertrophy [25]. Thus, transferring the FHL in the acute setting could help overcome deficiencies in plantarflexion strength and possibly compensate for the inferior mechanical properties of the ruptured AT by relocating the FHL tendon insertion to a more biomechanically advantageous site, i.e., near the insertion of the AT.

Endoscopic FHL transfer has been proposed as a treatment option for chronic, or failed, AT repairs [7, 22, 33] and acute complex ruptures [32]. Recently, Batista et al. published a prospective case series of patients with acute ATRs treated with endoscopic FHL transfers, with satisfactory results and minimal complications [6]. In this study, an isolated endoscopic FHL transfer was performed, regardless of rupture complexity or location.

Cost-effectiveness analysis (CEA) is a valuable tool to guide policymaking and help physicians, patients, and regulators make informed resource allocation decisions. Previous economic analyses regarding the treatment of acute ATRs have made comparisons between open surgery and conservative treatment [23, 27, 54, 55, 59], between open surgery, percutaneous surgery, functional treatment and immobilization [19], and between open and percutaneous surgery [11]. However, the cost-effectiveness potential of endoscopic FHL transfer remains to be evaluated. Early CEA is used to assess the likelihood of an intervention being cost-effective in different prospective scenarios [20], which is particularly important when designing clinical trials or developing new techniques or devices. The main advantage of early CEAs is assessing potential cost savings while new technologies are still being developed or in the early stages of introduction, which may be used to guide investment, research, or healthcare decisions. As they are being implemented in the early stages of development, early CEAs frequently rely on expert opinions, observational studies, or small clinical trials to define model parameters.

The objective of this study was to perform an early CEA of endoscopic FHL transfer in the setting of a complete acute rupture of the AT. This analysis compared the costs and benefits of endoscopic FHL transfers for acute ATRs with conservative treatment, open surgery, and minimally invasive surgery (MIS) in the health care sector and societal perspectives.

MATERIALS AND METHODS

This study was conducted according to the recommendations of the Second Panel on Cost-effectiveness in Health and Medicine [52].

Study context

This study's target population was patients aged 18 to 65 with acute ATRs. The following current treatments were considered: conservative treatment, open surgery, and MIS; complementary functional rehabilitation was assumed to be performed in all cases. The timeframe was two years. This study reports a reference case based on a societal perspective, meaning costs and health events are incorporated regardless of who pays and benefits [20]. Comparisons are made regarding incremental utilities, measured as Quality-Adjusted Life-Years (QALYs) and incremental costs.

Conceptual model

The conceptual model, created using a decision tree, aimed to outline the main possible health events during treatment of an acute ATR and the follow-up actions needed. The decision tree, shown in Figure 49, was made using the *web app* Lucidchart (Lucid Software Inc., South Jordan, Utah).

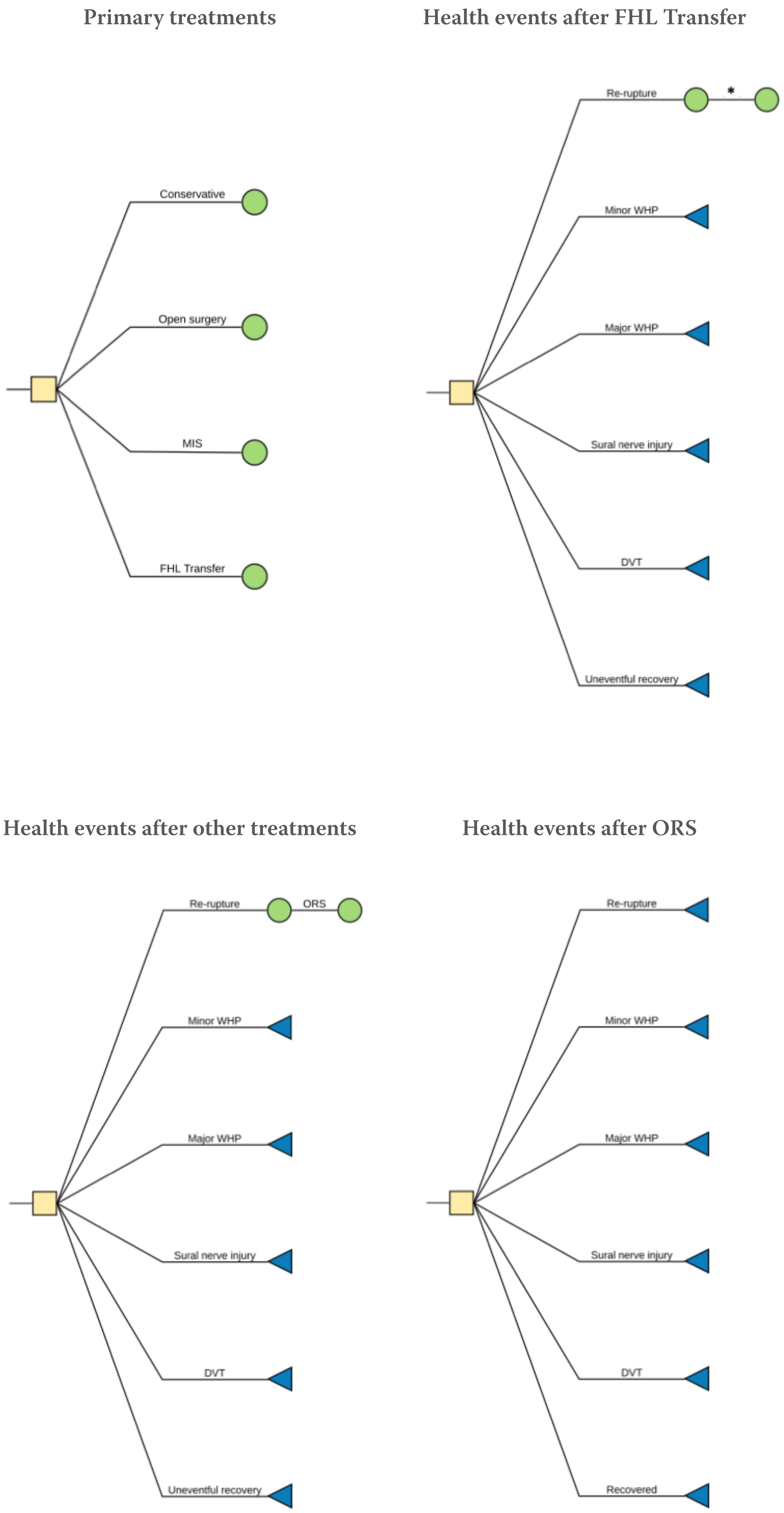


FIGURE 49 | Schematic representation of the decision tree. Nodes are represented by squares, circles, or triangles indicating a decision, uncertain event, or endpoint. Branches, represented by lines between or after a node, indicate clinical or health events. The health events after "revision open surgery" are the same after primary treatments. *: Re-ruptures after endoscopic flexor hallucis longus transfers are assumed to be treated conservatively. DVT: deep venous thrombosis. FHL: endoscopic flexor hallucis longus transfer. MIS: minimally invasive surgery. ORS: open revision surgery.

Patients were assumed to be treated in the acute setting without significant delays. Regardless of the treatment option selected, six main health events during/after treatment were considered: the patient recovered or had one of five complications. The five complications considered were: re-rupture; minor wound healing problems (WHPs) due to skin breakdown or superficial infection; major WHPs due to deep surgical infection and wound dehiscence, not amenable to conservative treatment; sural nerve injury; and deep venous thrombosis (DVT). These complications were chosen as main health events because their occurrence causes significant functional debilitation [58] or may require prolonged treatment. Patients suffering re-ruptures after the three current treatments were assumed to be treated with open revision surgery (ORS) as described by Nilsson-Helander et al. [41]. Re-ruptures after endoscopic FHL transfers were assumed to be treated conservatively [6]. Conservative treatment of re-ruptures after endoscopic FHL transfers was based on the assumption that the transferred tendon is not affected and on literature reports of treatment of chronic injuries or failed AT repairs using only this procedure with acceptable outcomes [7, 22, 33]. Previous studies of endoscopic FHL transfer for chronic ATRs treatment have not reported, to date, rupture of the transferred tendon [7, 22, 33, 56].

This conceptual model was developed into a Markov model, using MATLAB Release 2019a (The MathWorks, Inc., Natick, Massachusetts) to assess how a simulated cohort of 100,000 patients would be distributed. Complications were mutually exclusive and considered to occur in the first three months. Model assumptions regarding health events are shown in Table 23.

TABLE 23 | ASSUMPTIONS REGARDING TREATMENTS AND HEALTH EVENTS

NODE	ASSUMPTIONS
Treatment	Surgical treatments are assumed to produce similar utilities and costs regarding office visits, physical therapy, and sick leave.
Complications	Utilities are discounted by 10% or 20% in case of minor or major complications.
Re-ruptures	The time from primary treatment to re-rupture is similar between treatments. The number of office visits and physical therapy sessions is similar to primary treatments. Sick leave after re-rupture is similar to primary treatments.
Minor WHP	These complications do not have a lasting effect on outcomes.
Major WHP	Patients with major wound healing complications have significant decreases in outcomes.
Sural nerve injury	Patients with sural nerve injuries return to work simultaneously as those without these injuries [34].
DVT	No statistically significant differences exist regarding rates of return to work and treatment outcomes between patients with and without DVT [5].

DVT: deep venous thrombosis. WHP: wound healing problems.

Reference case

The model was parameterized using secondary data obtained from an extensive literature review. In addition, a systematic review of the literature was conducted to gather information on complication rates of current ATR treatments (see Appendix III). Only therapeutic studies with Level of Evidence 1, according to the Oxford Centre for Evidence-Based Medicine Levels of Evidence Working Group [44], were included. When applicable, data from multiple sources were combined using weighted averages. One researcher performed data collection, and another researcher cross-checked the extracted data.

Probabilities: Transition probabilities of current treatments were defined based on the seven papers included in the systematic review [21, 29, 35, 37, 42, 46, 60]. The study search and selection flowchart can be seen in Figure III-S1 (Appendix III). Studies' demographic and outcome data can also be found in Appendix III (Tables III-S1 and III-S2, respectively). Outcome data related to endoscopic FHL transfer was retrieved from the study by Batista et al. [6] (Table 25). Complication rates after ORS were retrieved from the study by Nilsson-Helander et al. [41]. Transition probabilities of current treatments, endoscopic FHL transfer, and ORS used for the reference case can be found in Table 24.

TABLE 24 | TRANSITION PROBABILITIES USED IN THE REFERENCE CASE AND ONE-WAY SENSITIVITY ANALYSIS

TREATMENT	UNEVENTFUL RECOVERY	RE-RUPTURE	MINOR WHP	MAJOR WHP	SURAL NERVE INJURIES	DVT
CT [21, 29, 35, 37, 42, 46, 60]	86.5%	10.2%	1.0%	0.0%	1.3%	1.0%
OS [21, 29, 35, 37, 42, 46, 60]	82.0%	2.3%	10.0%	0.7%	4.0%	1.0%
MIS [21, 35]	83.0%	2.4%	7.3%	0.0%	4.9%	2.4%
FHL [6]	92.8%	1.8%	3.6%	0.0%	0.0%	1.8%
ORS [41]	71.5%	0.0%	10.7%	3.6%	7.1%	7.1%

Transition probabilities were calculated using weighted means from the referenced studies for each outcome. CT: conservative treatment. DVT: deep venous thrombosis. FHL: endoscopic flexor hallucis longus transfer. MIS: minimally invasive surgery. OS: open surgery. ORS: open revision surgery. WHP: wound healing problem

TABLE 25 | PATIENT (N = 56) DEMOGRAPHICS AND OUTCOMES FROM THE STUDY BY BATISTA ET AL. 2020

PARAMETER	VALUE
PATIENT DEMOGRAPHICS	
SIDE	
Right	24 (42.9)
Left	32 (57.1)
RISK FACTORS	
None	38 (67.9)
Anticholesterol drugs	9 (16.1)
Hypertension	3 (5.4)
Overweight	2 (3.6)
Smoker	4 (7.1)
ACHILLES TENDON RUPTURE SITE	
Insertional	5 (8.9)
Proximal	21 (37.5)
Middle	18 (32.1)
Distal	12 (21.4)
AGE (YEARS)	
Mean ± SD	36.4 ± 8.1
Median (range)	35.5 (25.0 to 59.0)
FOLLOW-UP (MONTHS)	
Mean ± SD	27.5 ± 7.3
Median (range)	27.0 (18.0 to 43.0)
OUTCOMES AT 18 MONTHS	
AOFAS	
Median ± SD	95.4 ± 4.9
ATRS	
Median ± SD	95.2 ± 4.4
VAS	
Median ± SD	0.6 ± 0.9

Values are represented as numbers (%) except where specified otherwise. AOFAS: American Orthopaedic Foot & Ankle Society ankle-hindfoot score. ATRS: Achilles tendon total rupture score. SD: standard deviation. VAS: Visual analog pain scale.

Utilities: QALYs is a measure of disease burden that combines the health-related quality of life (HRQoL) and life expectancy. This measure varies between 0 and 1, where 0 represents "equal to being dead" and 1 represents one year of life in the best possible health state. The range of values for QALYs employed in this study follows patient-reported outcome measures obtained from the literature [13, 45, 46, 59]. Accordingly, utilities for patients treated conservatively, without further complications, were assumed to be, for the first three months, 3 to 6 months, and 6 to 24 months after injury, respectively, 0.74, 0.85, and 0.89 [13, 45, 46, 59]. For patients treated surgically (open surgery, MIS and FHL transfer) these were assumed to be 0.75, 0.87, and 0.93 [13, 45, 46, 59]. Since no experimental data is available on the effect of complications on treatment utilities, QALYs were discounted throughout the study's two-year timeframe by 10% or 20% in case of minor (sural nerve injuries and DVTs) or major complications (re-ruptures and major WHPs), respectively, based on reports of the effect of complications on treatment outcomes [9, 34, 48]. The utilities in patients with minor WHPs were not discounted. The current analysis is limited to the first two years, so the current model assumes that all the recovered patients have the same QALY utility for the rest of their life following the 24 months after treatment.

Costs: Cost items were defined for each node in the decision tree and were identified, whenever appropriate, through Current Procedural Terminology (CPT) codes selected from the literature [55] (Table III-S3, Appendix III). Quantities per cost item were defined based on previously published reports and this study's research team's clinical experience (Table III-S4, Appendix III) [3, 4, 8, 9, 11, 12, 15, 17, 23, 26, 28, 30, 31, 38, 39, 41, 47, 51, 53, 55, 59]. These quantities were explicitly defined for each node/item pair. Average prices of diagnostic and therapeutic procedures for the Boston, Massachusetts, area were extracted, during June 2021, from information publicly available on the FAIR Health Consumer website [18]. No specific cost value was found for the endoscopic FHL transfer; thus, the same procedure price for primary repairs was used in the reference case. The drug price ranges included in the model were extracted from the *Medicare Part D Drug Spending and Utilization* database [36]. Unitary prices for each cost item can be found in Appendix III (Table III-S5).

Costs related to time off work were calculated using the human capital method. This method focuses on the patient's perspective and productivity lost due to illness or injury. Productivity costs are calculated as the product of total hours lost and the hourly wage [20]. It was assumed that a healthy person works 42 hours per week, with a mean hourly wage of $27 (U.S. national average in 2019) [43], considering a societal perspective in an American setting. Time until return-to-work (RTW) after open and MIS surgical treatments were the same, as evidence suggests that open and MIS repairs provide similar outcomes [1]. Since specific values for patients subjected to endoscopic FHL transfers are currently unavailable, the same time until RTW for open and MIS surgeries was adopted. Time until RTW after revision surgery was considered to vary similarly to primary treatments because a specific average time until RTW could not be found. In the study by Nilsson-Helander et al., patients with sedentary occupations could RTW within one week of surgery, and 96.4% of patients could return to their activities within six months of the revision surgery [41], which is similar to what was considered for primary surgeries. Data regarding the time until RTW for each specific complication can be found in Appendix III (Table III-S4).

Costs were estimated in 2019 U.S. dollars at constant values. No capital discounting or inflation adjustment was applied, given the short duration of the study. The total cost of each treatment was computed using the following method: for each node, the cost items' costs were summed after multiplying each unitary cost by the assigned quantity; for each patient in the virtual cohort, the costs of the nodes representing the several treatments to which the patient was submitted were aggregated; and finally, the costs associated to the several patients of the virtual cohort were summed. The values used in the reference case model are summarized in Table III-S6 (Appendix III) under "Reference case."

Cost-effectiveness analysis

The main outcome used to determine the preferred strategy was the incremental cost-effectiveness ratio (ICER), defined as the ratio of differences between two treatments regarding utilities and costs. The ICER is calculated as:

$$ICER = \frac{Cost_{Treatment} - Cost_{Control}}{QALY_{Treatment} - QALY_{Control}}$$

where *Control* is the treatment with the lowest average total cost. The ICER represents the cost of one added QALY. For this study, a willingness-to-pay (WTP) threshold ICER of $100,000 per QALY was adopted, which is between one and two times the Gross Domestic Product per capita, as recommended by the World Health Organization for cost-effectiveness studies of health-related interventions in developed countries [14].

Other model outputs considered are average QALYs in the cohort, direct and indirect costs, and the net monetary benefit (NMB). The NMB is calculated as:

$$NMB = (Benefits * \lambda) - Costs$$

where is the WTP threshold. The incremental NMBs (ΔNMB) are calculated as the NMB for each surgical treatment less the NMB for the conservative treatment used as control.

Sensitivity analyses

Sensitivity analyses were performed to determine whether changes in input parameters would cause significant deviation from the reference case results.

Probabilistic sensitivity analysis

A probabilistic sensitivity analysis (PSA) was conducted to account for variation in model parameters around a central value and confirm model robustness. Therefore, Monte Carlo simulations were used to observe how the model responded to randomly generated multiple input variables for an *n* number of iterations. Model input parameters were randomly sampled for each iteration from probabilistic distributions derived from data found in the literature or the research team's clinical experience. The number of iterations was determined using the methodology proposed by Hatswell et al. [24]. The ΔNMBs were computed for each of the surgical treatments in each iteration. After each iteration, the 95% confidence interval (CI) for the ΔNMB of each surgical treatment was computed. A minimum of 1000 iterations were performed. The number of iterations was then progressively increased until CIs did not include zero. Random data sets were generated from probability distributions and fed into the model in each iteration. Beta distributions were used for complications rates, truncated normal distributions for utility metrics and hourly wages, and log-normal distributions for cost data. The cost-effectiveness acceptability curves for the surgical treatments were computed, estimating the probability of cost-effectiveness at different WTP thresholds.

One-way sensitivity analysis

A one-way sensitivity analysis was conducted by sequentially varying each model parameter within a given range, defined from the literature search, the research team's clinical experience, or a 25% variation from the reference case value. Model parameters used in the reference case and one-way sensitivity analysis can be found in Table III-S5 (Appendix III). The model was considered sensitive to a given parameter if: ICER varied more than $2000; ICER shifted from a value above to a value below the WTP threshold; or treatment rankings regarding ICERs, utilities, or costs were reordered. Model sensitivity to a parameter was calculated, per treatment, as the percentage change in the ICER from the reference case and presented as the average across the input value range. Values presented as outputs of this analysis are the model sensitivity to a given parameter and the threshold value of such parameter at which the ICER is below the WTP threshold (if applicable).

RESULTS

In the reference case, ICERs exceeded the WTP threshold for all the surgical approaches, using the conservative case as control. Results of the reference case analysis can be found in Table 26.

Primary treatment was the main cost driver for all the treatments, although costs with complications can represent as much as 10.1% in patients treated conservatively (Table III-S7, Appendix III). Conservative treatment also showed the most considerable cumulative costs and losses in QALYs due to complications (Figure 50).

TABLE 26 | RESULTS OF THE REFERENCE CASE ANALYSIS

TREATMENT	QALYS	COSTS		NMB#	ICER*
		DIRECT	INDIRECT		
Conservative	0.83 (0.53 to 0.87)	$9,736 ($8,605 to $26,721)	$1,609 ($1,343 to $6,272)	$71,656 ($20,057 to $76,678)	-
Open surgery	0.89 (0.53 to 0.90)	$16,940 ($16,458 to $34,574)	$1,564 ($1,448 to $6,377)	$70,057 ($11,548 to $72,094)	$128,766
MIS	0.88 (0.53 to 0.90)	$17,732 ($17,258 to $35,374)	$1,538 ($1,448 to $6,377)	$69,172 ($10,748 to $71,294)	$145,653
Endoscopic FHL transfer	0.89 (0.53 to 0.90)	$16,747 ($16,543 to $25,412)	$1,506 ($1,448 to $4,272)	$70,909 ($23,203 to $72,008)	$112,122

#: cost-effectiveness threshold of $100,000. *: calculated using conservative treatment as control treatment. ICER: incremental cost-effectiveness ratio, defined as the cost of one additional QALY for the reference case cohort. FHL: flexor hallucis longus. MIS: minimally invasive surgery. NMB: net monetary benefit. QALYs: quality-adjusted life-years. Values are represented as mean per patient and range, except otherwise specified.

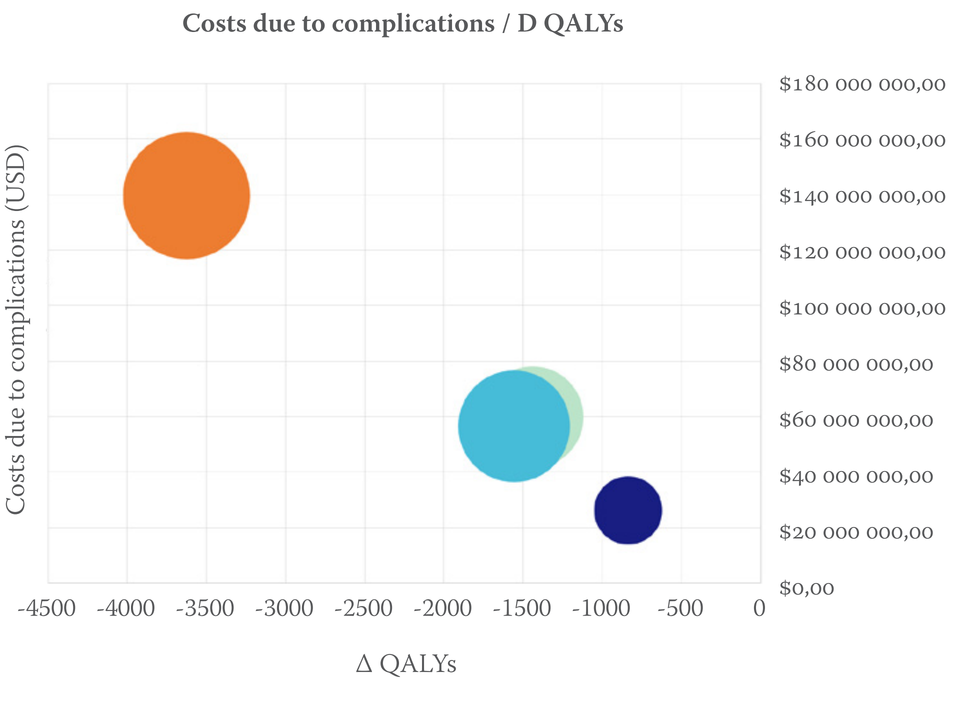


FIGURE 50 | Cumulative costs and losses in quality-adjusted life-years due to complications in the cohort of the reference case. The bubble size is directly proportional to the number of patients with complications. FHL: endoscopic flexor hallucis longus transfer. MIS: minimally invasive surgery. QALY: quality-adjusted life-years.

FIGURE 51 | Cost-effectiveness acceptability curve for surgical treatments. Probability of cost-effectiveness vs. willingness-to-pay (WTP). Vertical lines represent WTP thresholds. QALY: quality-adjusted life-years.

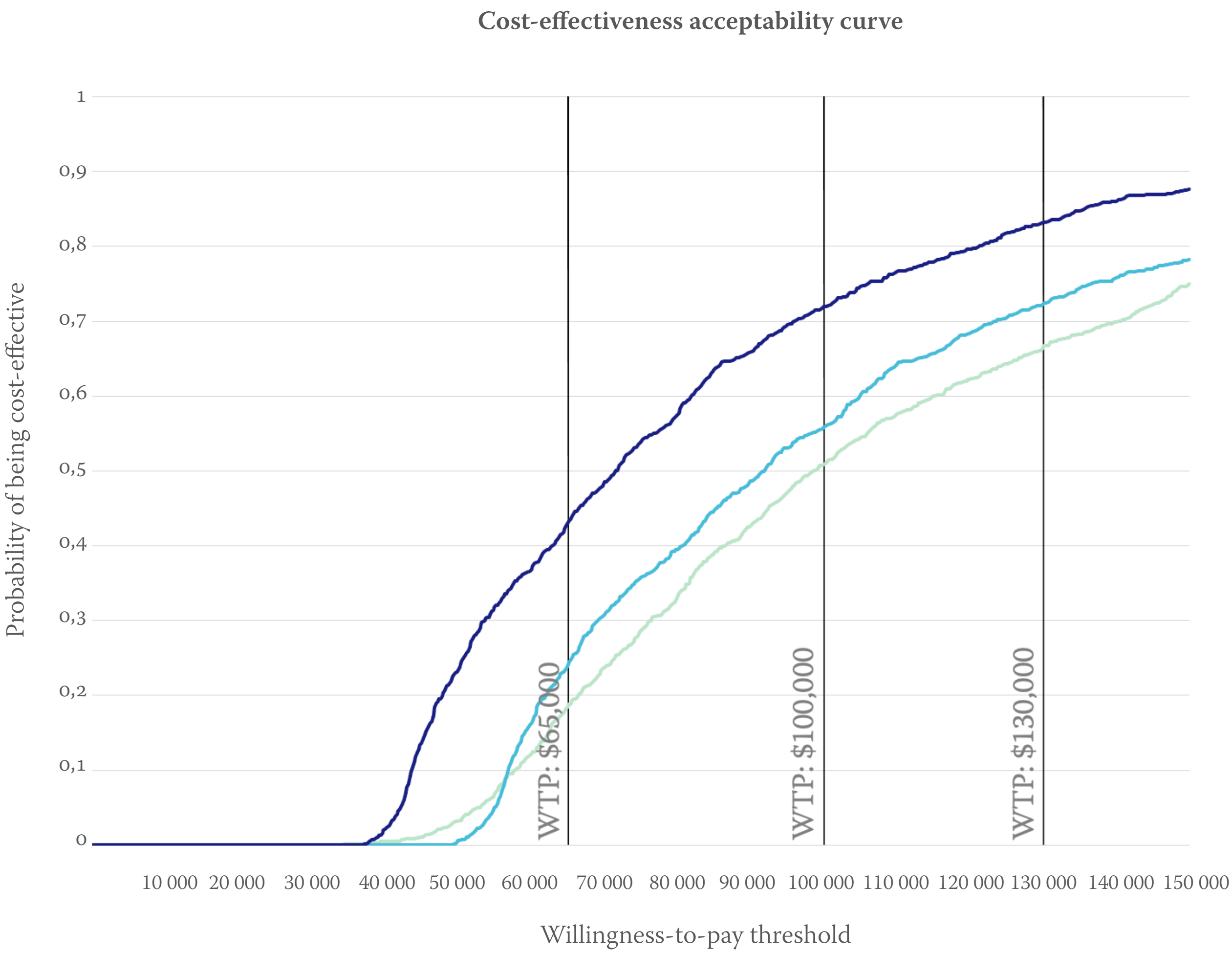
Open surgery

Minimally invasive surgery

Endoscopic FHL transfer

Probabilistic sensitivity analysis

A cost-effectiveness acceptability curve showing the probability of being cost-effective for the different WTP thresholds can be found in Figure 51. Convergence was obtained after 1,000 iterations (Figure III-S2, Appendix III). At a WTP threshold of $100,000, open surgery was cost-effective in 50.9%, MIS in 55.8%, and endoscopic FHL transfer in 72% of the iterations. The calculated costs for the reference case and PSA are comparable, both for primary treatment and for complications and their treatments (Figure III-S3, Appendix III). Open surgery was ranked the least cost-effective option in the PSA. Relative to other treatments, costs related to the treatment of complications and absence from work raised more in open surgery than in other treatments compared with the reference case.



One-way sensitivity analysis

The model was most sensitive to treatment utilities (QALYs, above 200% sensitivity) parameters, followed by the costs of primary treatment procedures (Figure 52). The specific minimal values for each parameter that made the ICER of a treatment sit below the WTP threshold are reported as threshold values and are shown in Table 27. Additional data regarding the results of the one-way sensitivity analysis can be found in Appendix III (Table III-S7).

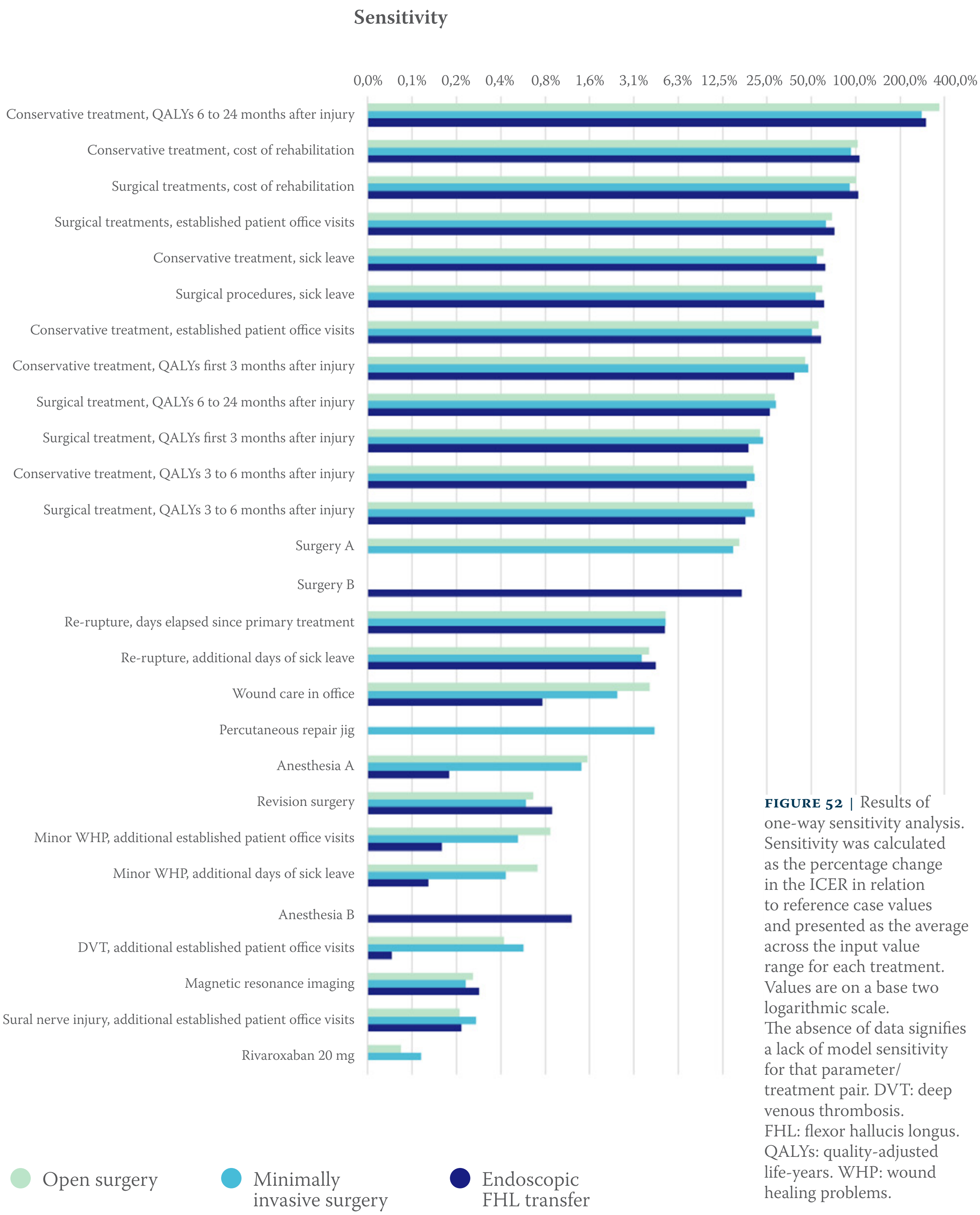


FIGURE 52 | Results of one-way sensitivity analysis. Sensitivity was calculated as the percentage change in the ICER in relation to reference case values and presented as the average across the input value range for each treatment. Values are on a base two logarithmic scale. The absence of data signifies a lack of model sensitivity for that parameter/ treatment pair. DVT: deep venous thrombosis. FHL: flexor hallucis longus. QALYs: quality-adjusted life-years. WHP: wound healing problems.

TABLE 27 | RESULTS OF THRESHOLD ANALYSES

	REFERENCE CASE	OPEN SURGERY	MINIMALLY INVASIVE SURGERY	ENDOSCOPIC FHL TRANSFER
Conservative treatment, established patient office visits	$3,405	$5,076	$5,965	$4,187
Surgical treatments, established patient office visits	$1,437	N/A	N/A	$629
Conservative treatment, cost of rehabilitation	$1,5678	$3,216	$4,077	$2,356
Surgical treatments, cost of rehabilitation	$1,113	N/A	N/A	$291
Surgery A	$9,341	$7,708	N/A	N/A
Surgery B	$9,341	N/A	N/A	$8,593
Conservative treatment, sick leave	$1,343	$2,995	$3,878	$2,112
Surgical procedures, sick leave	$1,448	N/A	N/A	$676
Conservative treatment, QALYs first 3 months after injury	0.74	0.67	0.63	0.71
Conservative treatment, QALYs 3 to 6 months after injury	0.85	0.72	0.64	0.79
Conservative treatment, QALYs 6 to 24 months after injury	0.89	0.86	0.85	0.88
Surgical treatment, QALYs 3 to 6 months after injury	0.87	1.00	N/A	0.93
Surgical treatment, QALYs 6 to 24 months after injury	0.93	0.95	0.97	0.94

Results of threshold analyses regarding parameters in which variation within the predefined range caused the increased cost-effectiveness ratio of a treatment to sit below the $100,000 willingness-to-pay threshold. Surgery A: primary Achilles tendon repair. Surgery B: endoscopic FHL transfer. FHL: flexor hallucis longus. N/A: not applicable. QALYs: quality-adjusted life-years.

DISCUSSION

The most important finding of this early CEA was that an endoscopic FHL transfer showed the highest likelihood among surgical techniques of being a cost-effective treatment in the setting of an acute ATR.

Previous economic analyses comparing surgery with conservative treatment have mostly reported that conservative treatment is a more cost-effective option [19, 23, 27, 54, 55] or that cost-effectiveness of surgical treatment is weakly supported [59]. These studies employed different conceptual frameworks, and only three reported WTP thresholds. In the study by Koltsov et al. [27], conservative treatment was the cost-effective option in 71.7% and 69.1% of the simulations at $50,000/QALY and $100,000/QALY WTP thresholds, respectively. In the study by Westin et al. [59], likelihood of surgery being cost-effective was 57%, 69%, and 73%, respectively, at WTP thresholds of €50,000, €80,000, and €100,000 per QALY. Minimally invasive surgery was cost-effective at a threshold of $100,000 in the study by Faucett et al. [19].

The critical difference in the abovementioned studies is the different HRQoL benefits attributed to conservative and surgical approaches. While Westin et al. [59] and Faucett et al. [19] assumed that surgery provided superior outcomes regarding QALYs, Koltsov et al. assumed that both treatments provided similar benefits [27], citing two randomized controlled trials as data sources [13, 46]. However, in one of the studies, while no statistical analyses directly comparing conservative and surgical treatments were performed, the HRQoL outcomes estimated were numerically different; with a median and an interquartile range, respectively, of 0.85 and 0.70 to 1.0 for the patients treated conservatively and 1.0 and 0.9 to 1.0 for the surgically treated patients [13]. Given the considerable model sensitivity to treatment benefits, it seems correct to attribute different treatment benefits even if these differences are small or without statistical significance.

The current study allocated the same benefits to endoscopic FHL transfer patients as other surgical treatments. However, prospectively collected data support the assumption that this treatment will provide at least similar benefits to the other surgical treatments [1, 6]. For example, the Achilles Tendon Total Rupture Score (ATRS) was higher, at a value of 95 ± 4.26, for endoscopic FHL transfer in the study by Batista et al. [6] than the values reported for open surgery by Olsson et al. [46], with ATRS value of 82 ± 20 and EQ-5D values of 0.91 ± 0.17. Therefore, future studies evaluating the HRQoL in patients subjected to endoscopic FHL transfers are of interest, especially considering that even a slight increase in QALYs after six months of surgery would render this treatment cost-effective. The same limitation applies to MIS, as benefits were assumed to equal those from open surgery. Regardless, current evidence supports the assumption of comparable patient-reported outcomes between these treatments, specifically between open and MIS [2] and between MIS and endoscopic FHL transfers [1].

The model herein assumes that patients treated in the acute setting with an endoscopic FHL transfer will not need revision surgery after re-rupture, which is supported by patient data [6]. Furthermore, studies have reported treating chronic injuries, or failed, AT repairs using only an endoscopic FHL transfer, with acceptable outcomes [7, 22, 33]. Regardless, one-way sensitivity analysis did not find this factor to be determinant, and thus this assumption may not significantly influence the outcomes of this study, possibly due to a relatively low number of re-ruptures in these patients. More studies are needed to evaluate the incidence and consequences of re-ruptures in this specific context.

A specific cost for endoscopic FHL transfer was not obtained because a CPT code for this procedure could not be identified. However, the direct cost of this procedure can be speculated to approximate that of an AT repair. Considering that the purpose of this study was to perform an early CEA, using the same direct costs of AT repairs as a starting point seemed a reasonable approach.

In the PSA, open surgery was the most expensive surgical treatment, despite having a lower ICER than MIS on the reference case. Accordingly, previous CEAs comparing open and MIS have deemed the latter more cost-effective [11, 19]. This difference in the cost-effectiveness ranking is due to subsequential costs of open surgery, which may be related to the treatment of complications. For example, albeit infrequent [8], complications such as major WHPs may require multiple surgeries or prolonged treatment [9] and significant time off work. Unfortunately, data related to the societal burden of complications related to ATRs is currently lacking, and certain approximations must be made. One key example is the duration of the sick leave after ORS. Here, it was considered that this parameter would vary similarly to primary surgeries, as it is stated in the referenced paper that patients with sedentary occupations were able to return to work one week after surgery, and 96.4% were able to RTW within six months, a time interval that is similar to that of primary surgeries without re-ruptures. However, even though the time range is similar, there is no guarantee that the probability distribution of time until RTW is similar between the two groups. Therefore, future research is needed to evaluate the costs and the utilities of complications related to ATRs.

Time until RTW after ATRs varies considerably in the literature [3, 4, 12, 15, 26, 28, 30, 38, 59]. In this study, an extensive literature search was performed to gather data regarding RTW after ATRs. Despite having the lowest upfront costs related to time off work, conservative treatment had the highest indirect costs, showing the complications' deleterious effect on a treatment's cost-effectiveness profile. Due to a lack of studies describing RTW for patients subjected to endoscopic FHL transfers, a similar time until RTW as in other surgical patients was assumed. In the study by Batista et al. [6], all patients returned to their previous activities within four months of treatment, which is comparable to those reported in other studies for MIS techniques [26, 30]. Future studies are needed to assess the time until RTW in patients treated with this approach for acute ATRs.

The main limitation of this study is the paucity of available data regarding endoscopic FHL transfers for treating ATRs in the acute setting. The early CEA model herein presented is based on a single prospective case series, and several modeling assumptions regarding the similarity between this approach and other surgical techniques had to be made. The results of the present study need to be considered in light of this limitation. Notwithstanding, even if this study's results may be, at best, considered preliminary, the framework developed herein may be helpful for future investigations.

The relatively short time horizon is also a limitation of this study. It should be noted that some complications, namely re-ruptures, may cause long-term deficits and decrease overall treatment benefits [58]. Therefore, it is possible that extending the model's time frame would cause surgical treatments to be cost-effective since patients submitted to these treatments showed higher overall health benefits due to a lower probability of re-ruptures than patients treated conservatively.

Finally, another limitation of this study is the lack of other non-healthcare sector costs in the model, such as those related to hiring replacements for workers on sick leave. Thus, it could be argued that adding these to the indirect costs of treatments could change outcomes since threshold analysis showed that a relatively small increase in the indirect costs of conservative treatment would change the cost-effectiveness ranking.

Clinical and research significance

Although several limitations can be recognized, as is inherent to early CEAs, some considerations can be made with clinical and research implications.

First, sensitivity analyses revealed that endoscopic FHL transfer has the highest likelihood among surgical approaches of being cost-effective. Given the current controversy between surgical repair and conservative treatment of ATRs, a different approach, with a promising cost-effectiveness profile, can be worth considering. Second, this study uncovers several research opportunities. For example, information on the HRQoL outcomes of MIS repairs and endoscopic FHL transfers is currently lacking.

CONCLUSION

Surgical treatments have a moderate likelihood of being cost-effective at a WTP threshold of $100,000, with endoscopic FHL transfer showing the highest likelihood. Interventions to improve HRQoL may be better suited for enhanced cost-effectiveness.

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Section Epsilon

Using advanced data analytics and machine learning models for prognostics in elite athletes

Chapter 10: Pre-injury performance is most important for predicting the level of match participation after Achilles tendon ruptures in elite soccer players: a study using a machine learning classifier

Chapter 11: Return-to-performance in elite soccer players after Achilles tendon ruptures: a study using a weighted plus/minus metric and matched-control analysis

CHAPTER 10

Pre-injury performance is most important for predicting the level of match participation after Achilles tendon ruptures in elite soccer players: a study using a machine learning classifier

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INTRODUCTION

Achilles tendon ruptures (ATR) are career-threatening injuries in elite soccer players. Unfortunately, despite a relatively high return to play (RTP) rate, 96%, according to Grassi et al. [11], 18% of players will not return to the same level of competition within two seasons following injury [34]. Furthermore, previous research has also shown that soccer players suffering from these injuries have their careers shortened, on average, by two seasons compared to matched controls [30].

Several studies reporting outcomes of ATRs in elite athletes are based on publicly available information [11, 13, 15, 24, 26, 30, 33, 34]. In soccer, one notable source is *transfermarkt.com* [10, 11, 16, 21, 34, 36], which has been considered accurate, regarding injury denomination and location, in 89% of cases [8, 16]. Although primarily aimed at aggregating player market values and transfer fees, it includes other valuable data for sports analytics, such as match results, player performance indicators (namely goals, assists, and fouls), and injury history. This database is publicly available and maintained by *transfermarkt.com* and its user community [32].

Artificial intelligence is a field that studies artificial agents that can mimic or surpass human-level intelligent tasks and has become increasingly popular in the past decade [7]. Machine Learning (ML) is a subset of artificial intelligence related to "advanced statistical techniques that use computer algorithms to model complex relationships between variables", with these computer algorithms *learning* automatically from *experience*, i.e., data, without direct human intervention [20]. These algorithms rely on data analysis models to uncover hidden patterns and other meaningful insights from large datasets [28]. Among these algorithms, one can find both unsupervised and supervised learning methods [1]. Unsupervised learning is used when "labels" are unavailable [1], i.e., individual instances in the dataset are not categorized. These algorithms can organize individual instances according to naturally emerging patterns in the dataset, detect anomalous patterns and perform dimensionality reduction [1, 7]. Supervised learning is used when data is "labeled", i.e., the algorithm is fed training data where individual instances – observations –and corresponding output values, obtained with human intervention, are known [1]. Regression and classification problems are the two main categories into which supervised learning can be divided [1, 7].

Despite recent advances in the characterization of consequences of ATRs for elite soccer players [10, 11, 30, 34], both an evaluation of how match participation evolves after injury and a set of prognostic tools to gauge the likelihood of return to the same level of play are still missing in the literature. In addition, previous studies of elite soccer players treated for ATRs have also been limited by their reduced number of cases under consideration [10, 30, 34], by being restricted to a single league [10, 30], or by missing performance measures besides the return to play at the same competitive level [11].

This study has a double objective. Firstly, an exploratory data analysis aims to inform athletes and staff how match participation evolves after ATRs. Secondly, it evaluates the performance of an ML model based on pre-injury features to predict whether a player would return to a similar level of match participation, together with a study of the most relevant features for this task.

MATERIALS AND METHODS

Player screening and selection

The website *transfermarkt.com* (Transfermarkt, Hamburg, Germany) was mined, between January and March of 2021, for relevant entries regarding soccer players who suffered an ATR while playing in first or second leagues.

A customized web scraper was developed using Scrapy [22]. Player screening and selection were carried out using the following scheme: firstly, a list of all first and second leagues across the world was manually compiled; secondly, team rosters for each team in each league, since season 2007/2008, were extracted to a list; finally, the injury data of each player in the list was retrieved. The resulting injury data was filtered for entries containing the string "Achilles tendon rupture" or "Achilles" combined with more than 90 days of absence. Another group of players with absence times of more than 90 days was built from the following strings: "calf", "leg", and "ankle tendon".

Each entry was then evaluated independently by two researchers. Only players with club reports, press releases, or interviews mentioning a complete ATR were eligible for inclusion. A minimum follow-up of 24 months was also required. Due to the COVID-19 pandemic and ensuing match calendar rearranging, only injuries occurring before March 31st of 2018 were included. Players that suffered partial or focal tears of the Achilles, and players that suffered an ATR while playing for teams not in first or second leagues, or were unaffiliated with any team at the moment of injury, were excluded. Disagreements were settled by discussion with a third researcher on a case-by-case basis.

Data extraction and dataset handling

The *transfermarkt.com* website was also scraped for the following items: date of birth, height, preferred foot, playing position, club transfers (including projected market values and transfer fees), whether the player had played for the national team (at any time during the player's career), date of clearance for unrestricted practice, and match participation data (as minutes on the playing field; for the season of injury, the preceding season, and the two seasons following injury). Specific match participation data included: minutes played, whether the player was in the starting team, whether the player did not play but sat on the bench, and the reason for not playing (medical injuries, coach choice, or other). Data were anonymized, pooled into a database, inspected, and formatted for consistency. In cases where players sustained bilateral ruptures, the first rupture was considered the index event.

Dealing with missing data

Missing data regarding minutes played per match were imputed using spline interpolation. In addition, missing values regarding categorical features related to match participation (reason for player absence from the playing field and whether the player was in the starting eleven) were imputed using backfilling. Of note, less than 0.01% of matches had missing information.

Feature engineering

The following features were computed from the available data: age at rupture, relative market value (obtained from the division of the player's market value by the squad total market value), whether a re-rupture or a contra-lateral rupture happened, whether there were other preceding or following Achilles tendon (AT) problems, date of the first official match participation following rupture, whether the player retired, changed clubs or was left without club within the two years following injury, minutes and matches played in the 24- (*Year -2*) and 12-months preceding (*Year -1*), and 12- (*Year 0*) and 24-months (*Year 1*) after injury. In addition, to account for discrepancies in playtime available, players' data related to match participation was averaged by the number of matches played by the team in 30-, 90-, 120-, 180- and 360-day intervals.

Additional feature engineering was then performed, leading to the creation of the following features: the player's market value multiplied by the average minutes played per match in *Year -1*, the market value of the team multiplied by the player's average minutes played per match in *Year -1*, the difference in minutes played per match in *Year -1* and *Year -2*, how many days had elapsed since the player joined the team when the injury happened and the number of months elapsed since the beginning of the season when the injury occurred.

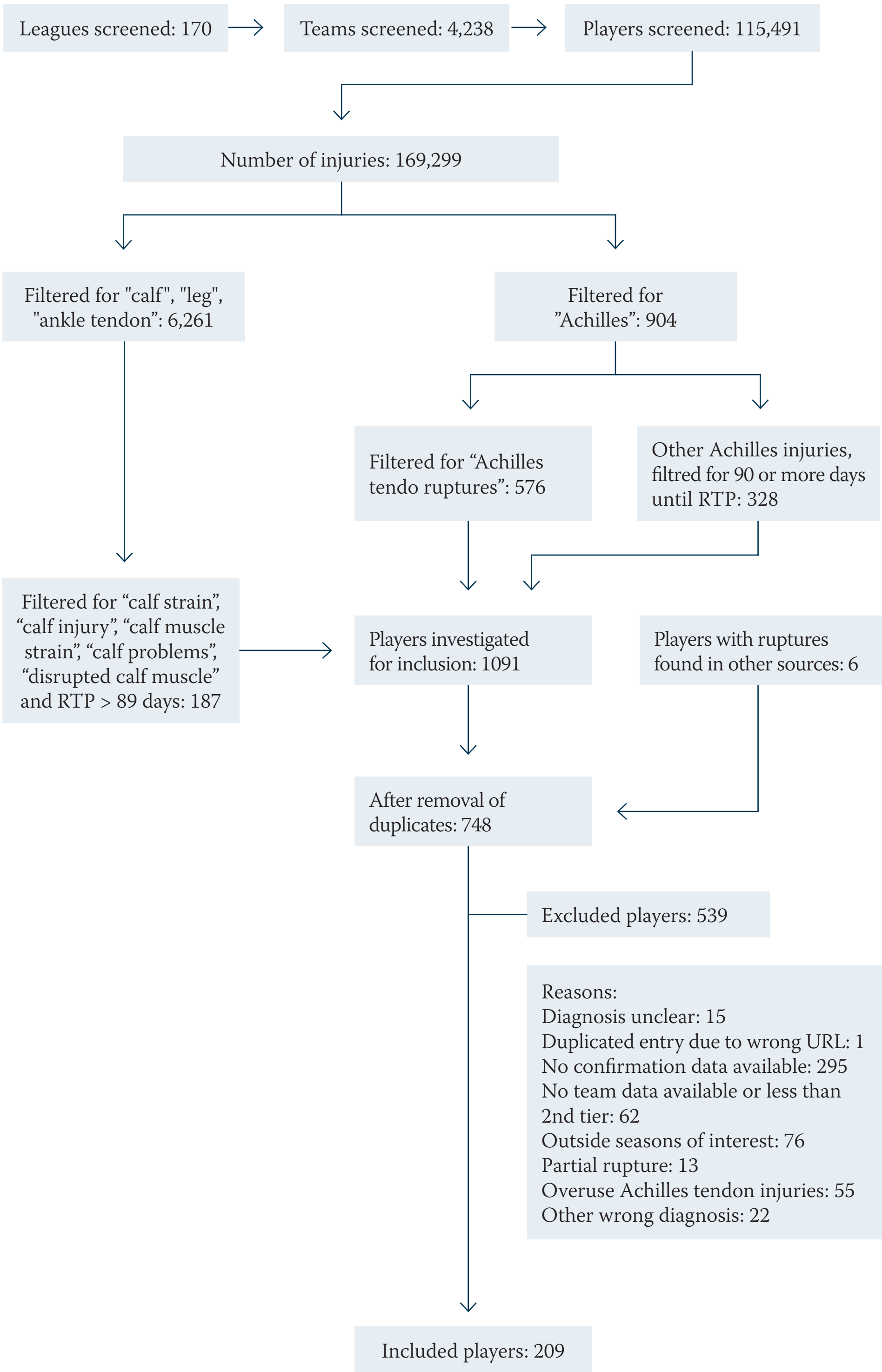
Machine learning model development and calibration

Unsupervised and supervised machine learning models were trained and evaluated using the Python *SciKit-Learn* library on the *Google Colab* platform [2, 25].

The difference between average minutes played per match during *Year 1* and *Year -1* (ΔMPM) was used to survey patterns in match participation after injury. Clustering analysis was performed using k-means clustering [1]. The optimal number of clusters was determined using the silhouette score [27], which varies between -1 and +1, and evaluates how similar data points are to their clusters compared to other clusters. A value of 0 represents overlapping clusters, and negative values signify that data points have been assigned to the wrong cluster. The silhouette score is frequently used to assess clustering quality, in the absence of a standard method in the research community [27]. Cluster stability was evaluated by repeatedly randomly dividing the main dataset into training and test datasets (number of repeats: 100; train/test split: 50/50) and measuring the similarity of the resulting clustering with the Adjusted Rand Index and Fowlkes-Mallows scores, using the main dataset cluster labels as ground truth.

The post-injury match participation level was predicted using the XGBoost classification algorithm [6, 12]. Continuous variables were scaled with standardization. Feature selection was performed using forward selection, in which the model is started with no features, and features are added sequentially and kept if results are improved. Model outputs were subjected to cross-validation using a ten k-fold strategy [19]. In a stratified ten k-fold cross-validation, 90% of the dataset is used to train, and 10% is used to evaluate the model. The procedure is repeated ten times, each with a different train/test split until the entire dataset has been used as the test set. The model was evaluated using the area under the receiver operating characteristic curve (AUROC) and Brier score loss. A representation of the machine learning processing pipeline can be found in Figure 53.

FIGURE 53 | Machine learning processing pipeline. AUROC: area under the receiver operating characteristic curve.



Statistical analysis

Statistical analysis was performed using Python libraries *Statsmodels* and *SciPy*. Except otherwise specified, values are presented as means and standard deviation. Groups were compared using Student's t-test, Kruskal-Wallis, or one-way ANOVA (depending on the number of groups and whether data followed a normal distribution). The assumption of normality was tested using the Shapiro-Wilk test. The Pearson's correlation coefficient was used to explore potential correlations between variables. Statistical significance was set at $p < 0.05$. Sample size calculation was not performed for this study.

RESULTS

The scraping process retrieved 748 entries. After applying exclusion criteria, 209 players were selected for analysis. Detailed information regarding the screening and selection process, with exclusion criteria, can be found in Figure 54.

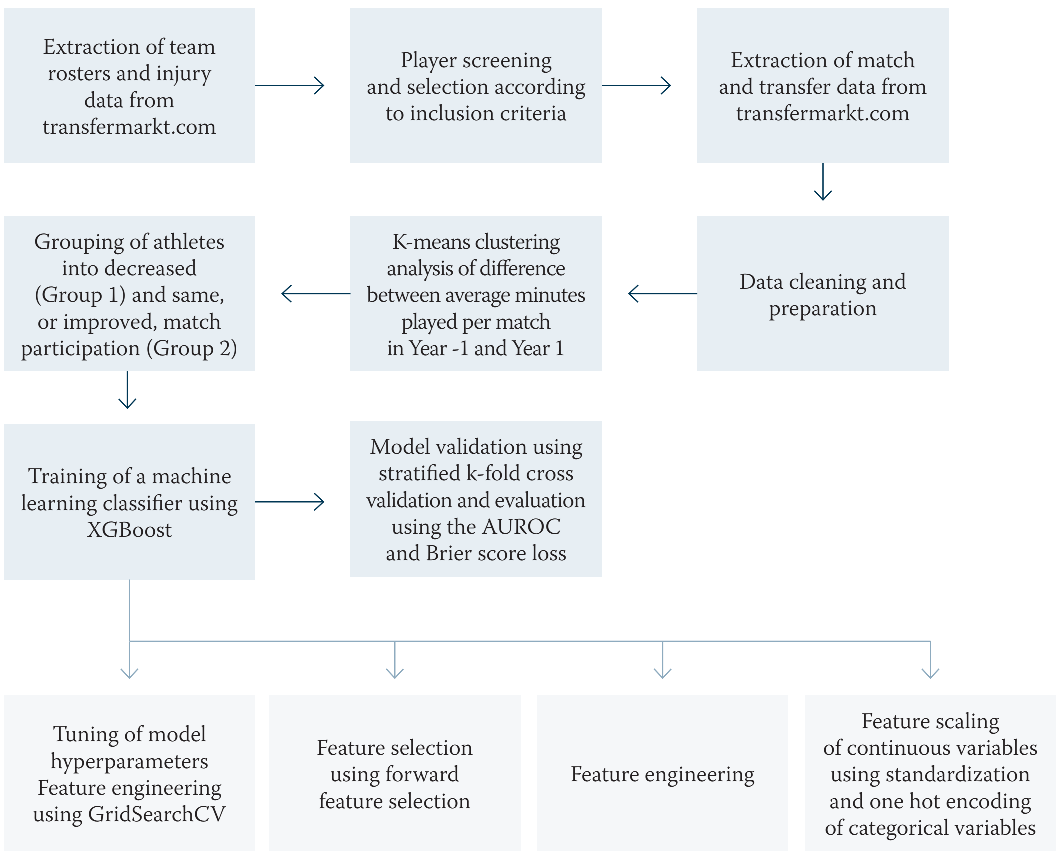


FIGURE 54 | Player screening and selection flowchart, with exclusion criteria.

Player demographics and baseline characteristics

Data related to player demographics and baseline characteristics can be found in Table 28. The mean age at rupture was 28.2 ± 4.0 years (range: 20 to 40).

TABLE 28 | PLAYER DEMOGRAPHICS AND BASELINE CHARACTERISTICS

		FORWARDS	MIDFIELDERS	DEFENDERS	GOALKEEPERS	TOTAL
N = (%)		55 (26.3)	43 (20.6)	95 (45.5)	16 (7.7)	209 (100)
Age, years		27.6 ± 3.7	28.6 ± 4.1	28.5 ± 4.0	28.6 ± 4.7	28.3 ± 4.0
Height, cm		181 ± 7	179 ± 7	184 ± 6	186 ± 5	182.2 ± 6.5
Preferred foot (%)	Right	38 (18.2)	36 (17.2)	67 (32.1)	14 (6.7)	155 (74.2)
	Left	14 (6.7)	5 (2.4)	26 (12.4)	2 (1.0)	47 (22.5)
	Both	3 (1.3)	2 (1.0)	2 (1.0)	0 (0)	7 (3.3)
League (%)	First	43 (20.6)	32 (15.3)	82 (39.2)	10 (4.8)	167 (79.9)
	Second	12 (5.7)	11 (5.3)	13 (6.2)	6 (2.9)	42 (20.1)
National team (%)	Yes	35 (16.8)	20 (9.5)	57 (27.3)	9 (4.3)	121 (57.9)
	No	20 (9.5)	23 (11.0)	38 (18.2)	7 (3.4)	88 (42.1)
World region (%)	Europe	48 (22.9)	33 (15.7)	69 (33.0)	12 (5.7)	162 (77.3)
	America	6 (2.9)	6 (2.9)	20 (9.5)	1 (0.5)	33 (15.8)
	Africa	1 (0.5)	2 (1.0)	6 (2.9)	1 (0.5)	10 (4.9)
	Asia/Australasia	0 (0)	2 (1.0)	0 (0)	2 (1.0)	4 (2.0)

Player demographics and baseline characteristics. Values are represented as means and standard deviations or percentages of total values.

Return to competition and career changes

Players were cleared for unrestricted practice after a mean of 223 ± 129 days (range: 92-1553). The first post-injury match was played after a mean of 287 ± 136 days (range: 106-825).

Fourteen players (6.7%) did not play any match after the AT injury and subsequently retired, with five more players retiring within two years after injury, for a total of 19 (9.1%). Three other players (1.4%) had their contracts expire and were left without a club sometime in the two years after injury. One-hundred and thirty players (62.2%) changed clubs within the two years following injury, with sixteen changing to teams playing below second league (7.7%).

Re-ruptures and other Achilles tendon issues

Ten players sustained re-ruptures (4.8%). These re-ruptures occurred after a mean of 621 ± 532 days after the index injury (153-1634). Six players (2.9%) sustained contra-lateral ruptures at some point in their careers. Eight players (3.8%) had a recording of previous AT problems, and 16 players (7.7%) had another time-loss injury (other than re-rupture or contra-lateral ATR) related to AT problems after the index injury.

Exploratory analysis of match participation data

Data from 32,853 matches were analyzed. The average minutes played per match was 48 ± 25 in *Year -2*, 46 ± 24 in *Year -1*, 11 ± 13 in *Year 0*, and 32 ± 25 in *Year 1*. Players were in the squad in 64.1 ± 26.2% of games in *Year -2*, 62.6 ± 25.0% in *Year -1*, 17.9 ± 18.1% in *Year 0*, and 47.0 ± 29.4% in *Year 1*. Players were in the starting eleven in 53.5 ± 28.0% of games in *Year -2*, 51.6 ± 27.0% in *Year -1*, 12.0 ± 15.1% in *Year 0*, and 35.3 ± 28.7% in *Year 1*. These differences were statistically significant ($p < 0.001$) for all comparisons except between *Year -2* and *Year -1*. A plot of average minutes played per match throughout the study time frame, computed in 30-day intervals for each playing position, can be seen in Figure 55.

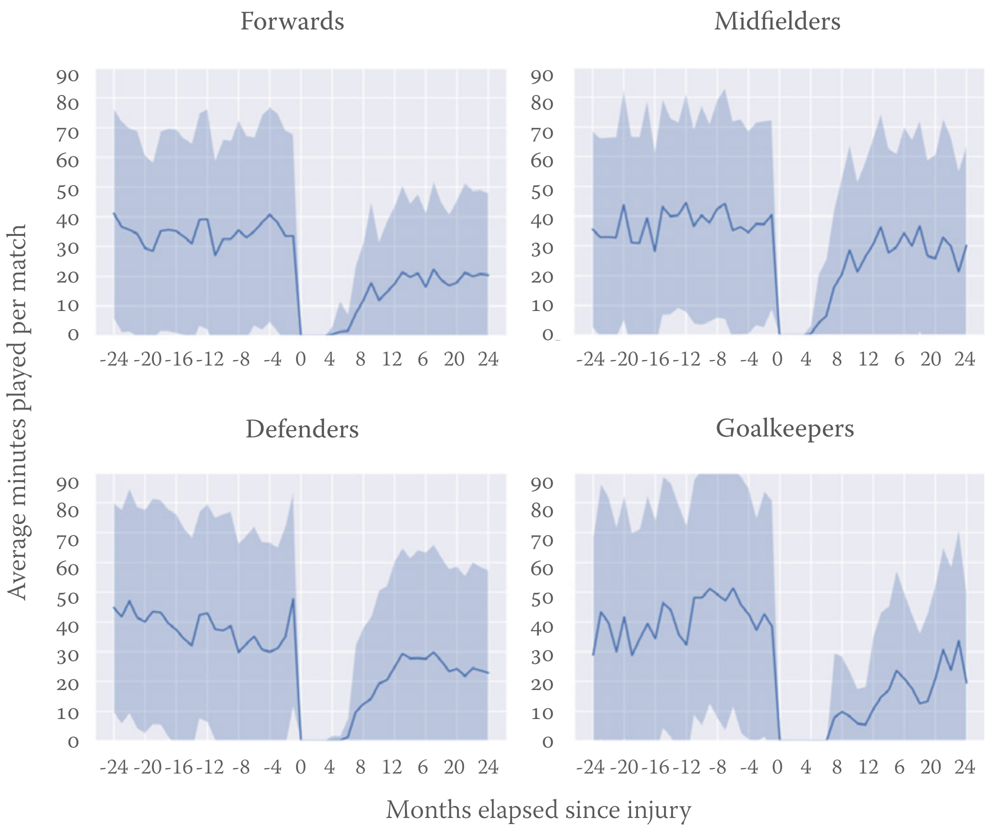


FIGURE 55 | Plot of average minutes played per match (y-axis) for all players included throughout the study time frame and computed in 30-day intervals (x-axis) per playing position. Shaded areas correspond to standard deviation.

The Pearson's correlation coefficient showed a small inverse correlation between days until clearance for unrestricted practice and the ΔMPM (r = -0.2; 95% confidence interval: -0.33 to -0.07; p < 0.01). A very small positive correlation was found between days elapsed since injury until first match played and the ΔMPM (r = 0.13; 95% confidence interval: -0.01 to 0.26; n.s.). After removal of outliers (those with values above 500 days; n = 18), this correlation was 0.2 (95% confidence interval: 0.06 to 0.33; p < 0.01). Finally, a small positive correlation was also found between the number of days from clearance for unrestricted practice to first match played and the ΔMPM (r = 0.24; 95% confidence interval: 0.11 to 0.36; p < 0.001).

Clustering analysis

The optimal number of clusters was four. The silhouette score was 0.55. The Adjusted Rand Index and Fowlkes-Mallows scores were 0.84 and 0.88, respectively. A plot of average minutes played per match for each cluster, computed in 30-day intervals, can be found in Figure 56. The main characteristics of clusters and respective statistical comparisons can be found in Table 29.

FIGURE 56 | Plot of average minutes played per match (y-axis) throughout the study time frame and computed in 30-day intervals (x-axis) for each cluster. Shaded areas correspond to standard deviation.

TABLE 29 | MAIN CHARACTERISTICS OF CLUSTERS AND STATISTICAL COMPARISONS

		CLUSTER A	CLUSTER B	CLUSTER C	CLUSTER D	p =
N = (%)		34 (16.2)	75 (35.9)	70 (33.5)	30 (14.4)	-
Age, years		29.9 ± 4.5	27.8 ± 3.8	28.6 ± 3.7	26.9 ± 3.9	0.02
Height, cm		184 ± 7	182 ± 6	181 ± 7	183 ± 6	(n.s.)
Position (%)	Forward	11 (32.3)	22 (29.3)	19 (27.1)	3 (10.0)	(n.s.)
	Midfielder	2 (5.9)	18 (24.0)	14 (20.00)	9 (30.0)	
	Defender	15 (44.1)	30 (40.0)	34 (48.6)	16 (53.3)	
	Goalkeeper	6 (17.7)	5 (6.7)	3 (4.3)	2 (6.7)	
Preferred foot (%)	Right	27 (79.4)	50 (66.7)	54 (77.1)	24 (80.0)	(n.s.)
	Left	5 (14.7)	23 (30.7)	14 (20.0)	5 (16.7)	
	Both	2 (5.9)	2 (2.6)	2 (2.9)	1 (3.3)	
League (%)	First	26 (76.5)	60 (80.0)	55 (78.6)	26 (86.7)	(n.s.)
	Second	8 (23.5)	15 (20.0)	15 (21.4)	4 (13.3)	
National team (%)	Yes	21 (61.8)	42 (56.0)	41 (58.6)	17 (56.7)	0.02
	No	13 (38.2)	33 (44.0)	29 (41.4)	13 (43.3)	
World region (%)	Europe	25 (73.5)	59 (78.7)	54 (77.1)	24 (80.0)	(n.s.)
	America	6 (17.7)	11 (14.7)	12 (17.2)	4 (13.3)	
	Africa	2 (5.9)	3 (4.0)	3 (4.3)	2 (6.7)	
	Asia/Australasia	1 (2.9)	2 (2.6)	1 (1.4)	0 (0.0)	
Market value (Euros)		1.2 ± 1.3 Mil	2.2 ± 4.0 Mil	1.7 ± 2.1 Mil	2.6 ± 3.8 Mil	(n.s.)
Time since joining the team (days)		1060± 1288	655 ± 769	658 ± 613	441 ± 549	0.01
Time between season start and injury (months)		6 ± 4	5 ± 4	5 ± 3	5 ± 4	(n.s.)
Previous AT injuries (%)	Yes	1 (2.9)	6 (8.0)	0 (0.0)	1 (3.3)	(n.s.)
	No	33 (97.1)	69 (92.0)	70 (100.0)	29 (96.7)	
Number of previous injuries (N =)		2.3 ± 1.5	3.0 ± 2.6	2.5 ± 2.3	2.8 ± 2.7	(n.s.)
Time until unrestricted practice (days)		280 ± 244	215 ± 118	202 ± 73	207 ± 55	(n.s.)
Time until first match (days)		242 ± 199	269 ± 137	271 ± 158	315 ± 119	0.05

Continuation of table 29

		CLUSTER A	CLUSTER B	CLUSTER C	CLUSTER D	p =
Average minutes played per match	*Year -2*	57 ± 28	47 ± 22	49 ± 26	40 ± 23	(n.s.)
	Year- 1	69 ± 14	48 ± 19	40 ± 25	27 ± 17	< 0.01
	Year 0	7 ± 9	10 ± 12	13 ± 15	12 ± 15	(n.s.)
	Year 1	10 ± 12	23 ± 19	40 ± 25	59 ± 19	< 0.01
Delta minutes played per match *Year 1* and *Year -1*		-59 ± 13	-25 ± 8	0 ± 8	32 ± 13	< 0.01
Re-rupture (%)	Yes	2 (5.9)	6 (8.0)	2 (2.9)	0 (0.0)	(n.s.)
	No	32 (94.1)	69 (92.0)	68 (97.1)	30 (100.0)	
Bilateral rupture (%)	Yes	1 (2.9)	2 (2.7)	3 (4.3)	0 (0.0)	(n.s.)
	No	33 (97.1)	73 (97.3)	67 (95.7)	30 (100.0)	
Other AT problems afterwards (%)	Yes	2 (5.9)	5 (6.7)	6 (8.6)	3 (10.0)	(n.s.)
	No	32 (94.1)	70 (93.3)	64 (91.4)	27 (90.0)	
Changed club within two years (%)	Yes	14 (41.2)	51 (68.0)	48 (68.6)	17 (56.7)	0.03
	No	20 (58.8)	24 (32.0)	22 (31.4)	13 (43.3)	
Left without club within two years (%)	Yes	1 (2.9)	2 (2.7)	0 (0.0)	0 (0.0)	(n.s.)
	No	33 (97.1)	73 (97.3)	70 (100.0)	30 (100.0)	
Retired within two years (%)	Yes	9 (26.5)	6 (8.0)	4 (5.7)	0 (0.0)	< 0.01
	No	25 (73.5)	69 (92.0)	66 (94.3)	30 (100.0)	

Comparison between clusters of match participation patterns. Values are represented as means and standard deviations or percentages of total values. AT: Achilles tendon. Clusters A, B, C and D relate to severe decrease, moderate decrease, maintenance or improvement of match participation.

Prediction of post-injury match participation

Players were divided into two groups based on whether they suffered a decrease in match participation while comparing average minutes per match in *Year 1* and *Year -1*. Players were assigned to Group 1 if they showed a decrease larger than 15 minutes played per match, and this difference was more than 20% of the value in *Year -1* (decreased match participation, n = 103). Otherwise, they were assigned to Group 2 (maintenance or improvement of match participation, n = 106). These designations were used as classification labels to train a ML classification algorithm. A list of included features and relative feature importance can be found in Table 30. After cross-validation, the average model AUROC was 0.81 ± 0.10, and the Brier score loss was 0.12.

TABLE 30 | FEATURES INCLUDED IN THE PREDICTIVE MODEL AND THEIR IMPORTANCE

BASE FEATURES	FEATURE IMPORTANCE
Days elapsed since joining the team	0.02
International level player?	0.02
Playing position	0.02
First or second league	0.01
Months elapsed since the beginning of the season when the injury occurred	0.01
Player market value	0.01
ENGINEERED FEATURES	**FEATURE IMPORTANCE**
Matches in which player was in the starting eleven divided by number of matches available, averaged in 30-day intervals, in Year -1	0.23
Minutes player per match, averaged in 30-day intervals, in Year -1	0.23
Matches in which player did not play because of medical issues divided by the number of matches available, averaged in 30-day intervals, in Year -1	0.15
Matches sat on bench divided by the number of matches available, averaged in 30-day intervals, in Year -1	0.12
Matches in the player's team won divided by the number of matches available, averaged in 180-day intervals, in Year -1 and Year -2	0.07
Player market value times minutes played per match in Year -1	0.04
Average minutes played per match in Year -1 divided by the same variable in Year -2	0.03
Team market value times days elapsed since player joined the team	0.02
Team market value times minutes played per match in Year -1	0.02

Features included in the predictive model. Engineered features result from combining continuous variables or mathematical operations between two other features. Feature importance relates to the relative contribution of that feature to the model, where higher values imply a higher impact on model performance.

DISCUSSION

The most important findings of this study were: most players gradually increased match participation during the first year after injury, with goalkeepers still improving after two years; and the ML classifier displayed good performance predicting whether a player would return to a similar, or even improved, level of match participation, with the most important features being related with pre-injury performance.

Plateauing of post-injury match participation occurred approximately one year after injury for forwards, midfielders, and defenders. Goalkeepers kept increasing playing time throughout the two years following injury, albeit at a slower rate. Of note, previous research has shown that outcomes after ATRs improve for at least one year after injury [3, 4], possibly due to a need to adapt to biomechanical changes in the lower limb resulting from tendon elongation [9]. Another critical aspect to consider is that psychological factors may be involved [29, 35], in which players need to regain confidence in their abilities and overcome the fear of re-injury.

Differences in match participation between *Year -1* and *Year 1* were the subject of clustering analysis. A silhouette score of 0.55 was found for the optimum number of clusters, which denotes moderate cluster separability. In addition, good clustering stability was found through the Adjusted Rand Index and Fowlkes-Mallows scores, meaning that these clusters were relatively consistent, even when only subsections of the dataset were randomly evaluated.

Younger age has been previously recognized as a favorable prognostic factor after ATRs in soccer players [10]. However, this point is controversial since other studies have not found statistically significant differences regarding age in players with favorable *versus* unfavorable outcomes in soccer [34], American football [24], basketball [15], and baseball [26]. In this study, the average age was lower in clusters C and D (maintenance or improvement of match participation) than clusters A and B (decreased match participation).

The number of days the player has been with the team at the time of injury is a previously unrecognized prognostic factor in ATRs. In this study, it was found that players in Cluster A were with the team for a significantly longer time (1060.1 ± 1287.6 days) compared with the remaining cohort ($p < 0.01$). The longer time with the team (or since the last market transfer) may signal a different career context for these players. For example, their contracts may be near expiration, and prospects of joining another team are dim. Coincidentally, players in this cluster also retired within two years in a statistically significant higher proportion than the remaining cohort (26.5% *versus* 5.7%; $p < 0.01$).

Players in cluster D took a significantly longer time before playing their first official match compared with the remaining cohort (315 days ± 119 *versus* 264 days ± 159; $p < 0.05$), despite similar time intervals from injury to unrestricted practice (207 days ± 55 *versus* 222 days ± 140; $p = 0.72$). Therefore, it can be speculated that by allowing these players more time to recover, they made their comeback at a higher performance level – closer to the full recovery potential –, which would be perceived as a superior recovery from injury, encouraging increased match participation. In addition, players in Cluster A (those with the most significant decrease in average minutes played per match in *Year 1* compared to *Year -1*) showed the shortest time until first match played. However, statistical correlations between days until unrestricted practice or first match played and the ΔMPM were small (albeit statistically significant). Further research is required to determine how a delayed return to competition may relate to improved outcomes after ATRs.

A ML classifier was trained, with an AUROC of 0.81 ± 0.10 after cross-validation, through careful feature engineering and selection, which translates as good discriminating performance [23]. The model's performance was also evaluated regarding output probabilities using the Brier score loss, as it was deemed helpful for players and staff to gauge these against their individual beliefs and experiences. It should be noted that only pre-injury features were used to train the model, and no data regarding treatments was available. Of note, since features related to pre-injury match participation showed the highest feature importance, it can be inferred that the future level of match participation is related to the sporting context at the time of injury, directly or indirectly (e.g., a tendency for early RTP in high-performing players which may reflect negatively in match participation afterward).

The use of ML algorithms to predict sports injuries is a current trend in research [14, 17, 31], but practitioners should remain cautious regarding their use despite recent advances. There are ethical implications to consider [5], such as inadvertently hindering a player's career through a wrongfully attributed worse prognosis. Model results may also be overly optimistic, either due to *overfitting* (when the model is fitted too close to a particular set of data and becomes unable to make good predictions in a generalized environment) or accidental *data leakage* (when information contained in the test set is wrongfully fed to the model during training). Nevertheless, the increasing accessibility and ease of use of ML tools and development frameworks offer an excellent opportunity to improve the care of musculoskeletal injuries, though researchers and clinicians should stay vigilant about its shortcomings.

The main limitation of this study is the inability to confirm the diagnosis. However, all included cases were manually double-checked using other sources by two researchers independently to avoid the inclusion of misclassified injuries. Other limitations are the unknown measurement accuracy of match participation data found on *transfermarkt.com*, the unavailability of treatment data, and the lack of a *strictu sensu* measure of player performance.

This study can guide the objectives and expectations of athletes and staff regarding how match participation evolves after an ATR, noting that it takes approximately one year to reach its peak (except for goalkeepers, who may keep improving for at least two years). In addition, the cluster of players with improved match performance showed a statistically significant increase in the number of days until first match played compared to the remaining cohort. Also, a small but statistically significant positive correlation was found between time until first match played and the ΔMPM. Finally, recent research has shown improved outcomes in patients undergoing *slowed-down* rehabilitation programs [18]. Thus, it may make sense to prioritize recovery of lower limb strength and sport-specific skills over an early return to competition.

CONCLUSION

Exploratory data analysis revealed that forwards, midfielders and defenders increased match participation during the first year after injury, with goalkeepers still improving at two years. Good performance was attained using a ML classifier to predict the level of match participation following an ATR, with features related to pre-injury match participation displaying the highest importance.

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CHAPTER 11

Return-to-performance in elite soccer players after Achilles tendon ruptures: a study using a weighted plus/minus metric and matched-control analysis

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INTRODUCTION

Achilles tendon ruptures (ATRs) can have a devastating impact on an elite soccer player's career. Previous research has shown that a significant portion of athletes suffering from these injuries shows poor sports performance after return-to-play (RTP) [3, 9, 31, 33], manifesting as decreased match participation and shortened careers, which may result from persistent symptoms [7], decreased strength [35], changes in lower limb biomechanics [4], psychological factors [30], and loss of space in the team owning to prolonged time off the pitch.

Because high case load of injuries in elite athletes is uncommon in the clinical setting, the use of public sources of information is a common practice in research aimed at assessing the consequences of injuries in this population [3, 5, 6, 9, 21, 22, 26, 31, 33]. Transfermarkt.com is a particularly noteworthy source, and, while it is primarily aimed at reporting club transfers, it also contains pertinent data for clinical and sports analytics, such as injury reports, match outcomes and player match participation data [32]. Furthermore, prior studies have confirmed the accuracy of this website in correctly identifying the type and location of injuries in 89% of instances [23].

Previous studies on ATRs using such an approach have focused mostly on whether players returned to similar competitive levels [3, 9], minutes played per match (MPM) [3, 5, 31, 33], or generic performance markers, such as games started [3, 33], or goals scored [5, 31, 33]. What is currently missing from the literature is the use of a true performance metric while assessing the consequences of ATRs in elite footballers. Unfortunately, despite several attempts [17, 24], there is no universally accepted individual performance metric in soccer.

Plus/minus (PM) metrics provide a practical and objective approach to player performance assessment and are commonly used in other sports, such as American football [26], and basketball [22]. In a nutshell, these metrics summarize the positive and negative effects a player has on the match outcome depending on whether he or she is playing or not [17]. In its simplest form, PM metrics can be calculated by dividing each differential in the target metric occurring in a match, e.g., goals scored, by the corresponding number of minutes that player was on the pitch.

In addition, to track the player's net performance throughout the season, the results of multiple matches may be combined.

Thus, to help clarify the effect of ATRs on individual player performance, the objective of this study was to quantify and compare individual player performance variations in players with and without ATRs in elite football leagues worldwide.

MATERIALS AND METHODS

This study employs a previously reported framework for data acquisition and analysis, with the details being reported elsewhere [3]. Briefly, the website Transfermarkt.com was scraped for player and team data, regarding player demographics, injuries, club transfers and match participation, and team match results and reports, namely number of goals scored and suffered and their timing in the match.

The ATR group in the present study consisted of soccer players that suffered ATRs while playing first- or second-tier leagues, without major time loss injuries in the first year following rupture. In accordance with previous guidelines for epidemiological studies [10], a major time loss injury was any injury causing a reported absence above 28 days. Furthermore, only athletes in which evidence towards having suffered an ATR could be verified in sources other than Transfermarkt.com were included. Athletes that did not RTP within one year following injury were excluded, as were those that retired or were left without a club in the two-years post-ATR.

A matched-control group (CTRL) was constituted by players of similar playing position, age, height and, whenever possible, competing in the same league as the study subject. Six controls per study subject were selected, with the same control being allowed in more than one comparison. Non-contemporary controls were also allowed, i.e., players whose data came from seasons different than the experimental subject. Potential control athletes were retrieved from the initial database used to screen for ATRs and correspond to players active between 2007 and 2018. Similarly to the ATR group, these athletes were excluded if they suffered a major time loss injury in the timeframe of interest.

Analysis of match participation

Match participation in the ATR group was compared to the CTRL group. The day of injury was considered "time zero" for both groups, and, thus, for each subject-control comparison the same time of year was considered, even if pertaining to different years, to ensure a similar competitive context, namely match congestion and weather conditions. Year -1 corresponds to the 360 days preceding injury, Year 0 to the 360-day interval following injury, and Year 1 to interval between 360 and 720 days after.

Comparisons were made regarding matches played, matches in which the athlete was in the starting eleven and average and cumulative MPM in 30- and 360-day intervals. Reasons for match absence were categorized into: "medical issues", "coaching decisions" and "other". This categorization was based on the information available from the Transfermarkt.com website and included in the player match participation page. If in any given match in which the player was not in the squad an injury had been recorded, it was assumed that the injury caused the player's absence from the squad. If the player sat in the bench but did not play any minutes or if the player was not in the squad and no comment was explicit, it was assumed to be a "coaching decision". Conversely, if a commentary, related, for example, to disciplinary action or player being called national team play, it was categorized as "other". Comparisons of matches lost due to "medical issues" were performed both in absolute and adjusted to match exposure terms, as recommended elsewhere [10].

Analysis of player performance

To evaluate individual player performance, we used a modified version of the weighted PM metric proposed by Schultze and Wellbrock [29]. This metric is calculated on a per minute basis using the following formula:

$$pm_x(t,w) = \sum_{w=1}^{W} \sum_{t=1}^{T} \left\{ \left[\left(\frac{wp_w^{Opp} - wp_w^{Own}}{T_w} \right) + \left(\Delta goals_{t,w} - \Delta goals_{t-1,w} \right) \times \left(\frac{2}{1 + \left| \Delta goals_{t,w} \right| - \left| \Delta goals_{t-1,w} \right|} \right) \right] \times on_{w,t}^{x} \right\} \quad (1)$$

where, T is the total number of minutes available in the match, w is week of the game (as in a season has W weeks), t is the minute in match play, wp^{Opp} and wp^{Own} are the opposing and the player's team winning probabilities, respectively, and $\Delta goals$ is the goal differential between the opposing and the player's teams. In the original description of this metric, the researchers used betting quotas from Bet365.com for the team's winning probabilities. Because the population included in this study represents a worldwide distribution and not all teams and matches could be found in the bookmaker's offers in a practical way, it was decided to compile all the matches available and perform an empirical calculation of the winning probabilities for each team, depending on whether said team was playing home or away, using a database of more than 500,000 matches. Finally, the whole performance analysis computation is multiplied by 1 if the player is in the pitch, or 0 if otherwise $on_{W,t}^{x}$.

Individual player performance was calculated for all matches played for the athlete's main team (meaning that matches played for national teams or reserves were excluded from the performance analysis) and summed in 30- and 360-days intervals. For purposes of ATR versus CTRL group comparisons, only data from Year -1 and Year 1 were used.

Statistical analysis

Statistical evaluation was conducted using the Statsmodels and SciPy libraries in Python. Mean and standard deviation values were reported for variables that followed a normal distribution, while median and interquartile range (IQR) were used if otherwise. Depending on the number of groups and data distribution, comparisons were made using Student's t-test, Mann-Whitney U, or one-way ANOVA. The Shapiro-Wilk test was used to check the normality assumption. To investigate any possible relationships between variables, the Pearson's correlation coefficient was used. The threshold for statistical significance was established at $p < 0.05$. This study did not include a sample size calculation.

RESULTS

After exclusion criteria, 125 athletes were included in the ATR group. Detailed information about the screening and selection process, including exclusion criteria, is shown in Figure 57. Thus, the CTRL group comprised 750 players. Player demographics and baseline characteristics can be found in Table 31.

TABLE 31 | PLAYER DEMOGRAPHICS FOR THE ACHILLES TENDON RUPTURE AND MATCHED-CONTROL GROUPS

	FORWARDS			MIDFIELDERS			DEFENDERS			GOALKEEPERS		
	ATR	CTRL	p	ATR	CTRL	p	ATR	CTRL	p	ATR	CTRL	p
N =	48	288		33	198		35	210		9	54	
Age, years	28.1 (5.1)	27.9 (5.1)	n.s.	28.0 (4.6)	27.7 (3.6)	n.s.	28.5 (6.0)	27.8 (4.1)	n.s.	30.5 (6.2)	29.4 (8.0)	n.s.
Height, cm	181 (10)	181 (8)	n.s.	178 (9)	180 (7)	n.s.	184 (7)	183 (10)	n.s.	183 (4)	187 (3)	n.s.

Player demographics for the Achilles tendon rupture (ATR) and matched-control (CTRL) groups.
Statistical significance set at $p < 0.05$. All values expressed as medians and interquartile ranges.
n.s.: without statistical significance.

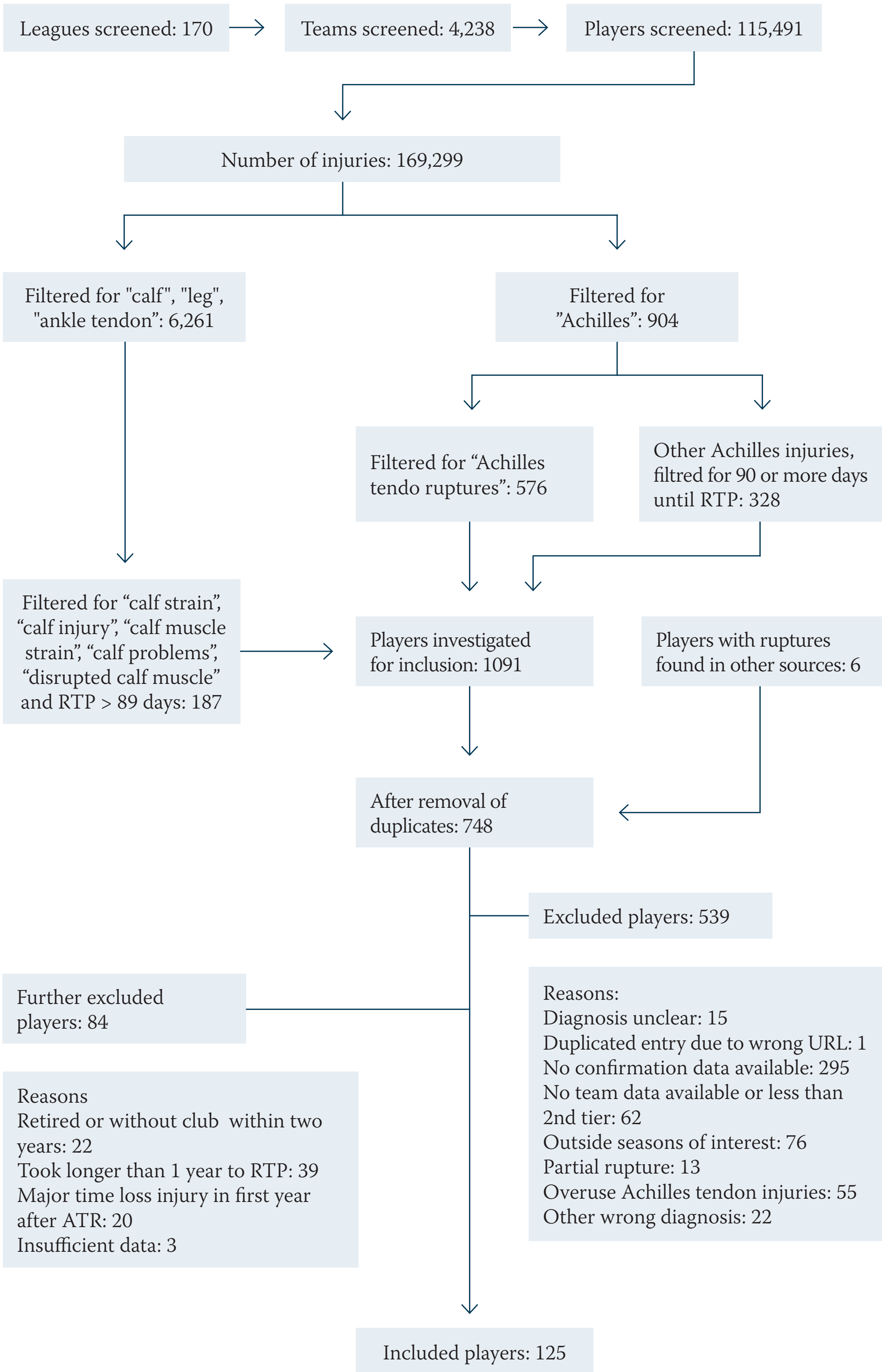

FIGURE 57 | Player screening and selection flowchart, with exclusion criteria.

Analysis of match participation

Data from 79,825 matches were analyzed. The number of matches available for analysis was not statistically significantly different between the ATR and CTRL groups from Year -1 through Year 1. Data related to match participation and reasons for match absence can be found in Table 32. In the ATR group, statistically significant differences between Year -1 and Year 1 were found for average MPM, matches played, matches started, matches sat in the bench, but not for reasons regarding match absence. Statistically significant differences between Year -1 and Year 1 were found for the CTRL group regarding reasons for match absence. A plot of average MPM throughout the study time frame, computed in 30-day intervals per playing position, for both groups, can be seen in Figure 58.

TABLE 32 | Comparison between the Achilles tendon rupture and matched-control groups regarding match participation

	YEAR -1			YEAR 0			YEAR 1		
	ATR	CTRL	p	ATR	CTRL	p	ATR	CTRL	p
Average MPM, minutes	46 (30)	52 (33)	n.s.	11 (18)	55 (34)	< 0.01	37 (37)	51 (34)	< 0.01
Matches sat in bench, %	6 (16)	6 (13)	n.s.	5 (9)	6(10)	n.s.	9 (17)	6 (12)	0.01
Matches started, %	52 (36)	59 (38)	n.s.	12 (20)	62 (39)	< 0.01	40 (42)	60 (39)	< 0.01
Matches played, %	65 (36)	70 (32)	n.s.	21 (23)	73 (28)	< 0.01	56 (38)	71 (29)	< 0.01
REASONS FOR MATCH ABSENCE									
Coach choice	100 (40)	95 (44)	n.s.	20 (23)	100 (35)	< 0.01	100 (33)	88 (61)	0.03
Medical issues	0 (33)	0 (25)	n.s.	79 (23)	0 (13)	< 0.01	0 (24)	0 (44)	n.s.
Other	0 (0)	0 (0)	n.s.	0 (0)	0 (7)	< 0.01	0 (0)	0 (0)	0.01

Comparison between the Achilles tendon rupture (ATR) and matched-control (CTRL) groups regarding match participation and reasons for match absence. Statistical significance set at $p < 0.05$. All values expressed as medians and interquartile ranges. MPM: minutes played per match; n.s.: without statistical significance.

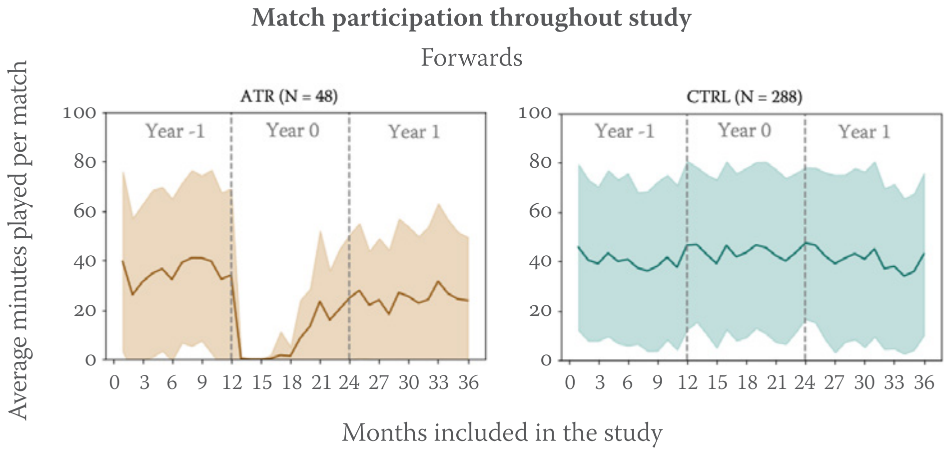

FIGURE 58 | Plot of average minutes played per match (y-axis) for all players included throughout the study time frame and computed in 30-day intervals (x-axis) per group and playing position. Shaded areas correspond to standard deviation. ATR: Achilles tendon rupture group. CTRL: matched-control group.

Analysis of match performance

Data from 76,464 matches was included in the performance calculation. Data was missing in 391 matches (0.5%), which was imputed using the player's mean performance per match for the study period. No statistically significant differences were found regarding the number of matches included in any year between the ATR group and the CTRL group. Net weighted PM metric per year, player position and study group can be found in Table 33. No statistically significant differences were found regarding net weighted PM metric per player position between Year -1 and Year 1. A plot of the computed metric throughout the study time frame, computed in 30-day intervals per playing position, for both groups, can be seen in Figure 59. A heatmap of statistical correlations between variables and performance in Year 1 for the ATR group per playing position can be found in Figure 60. Confidence intervals for statistically significant correlations can be found in Table 34.

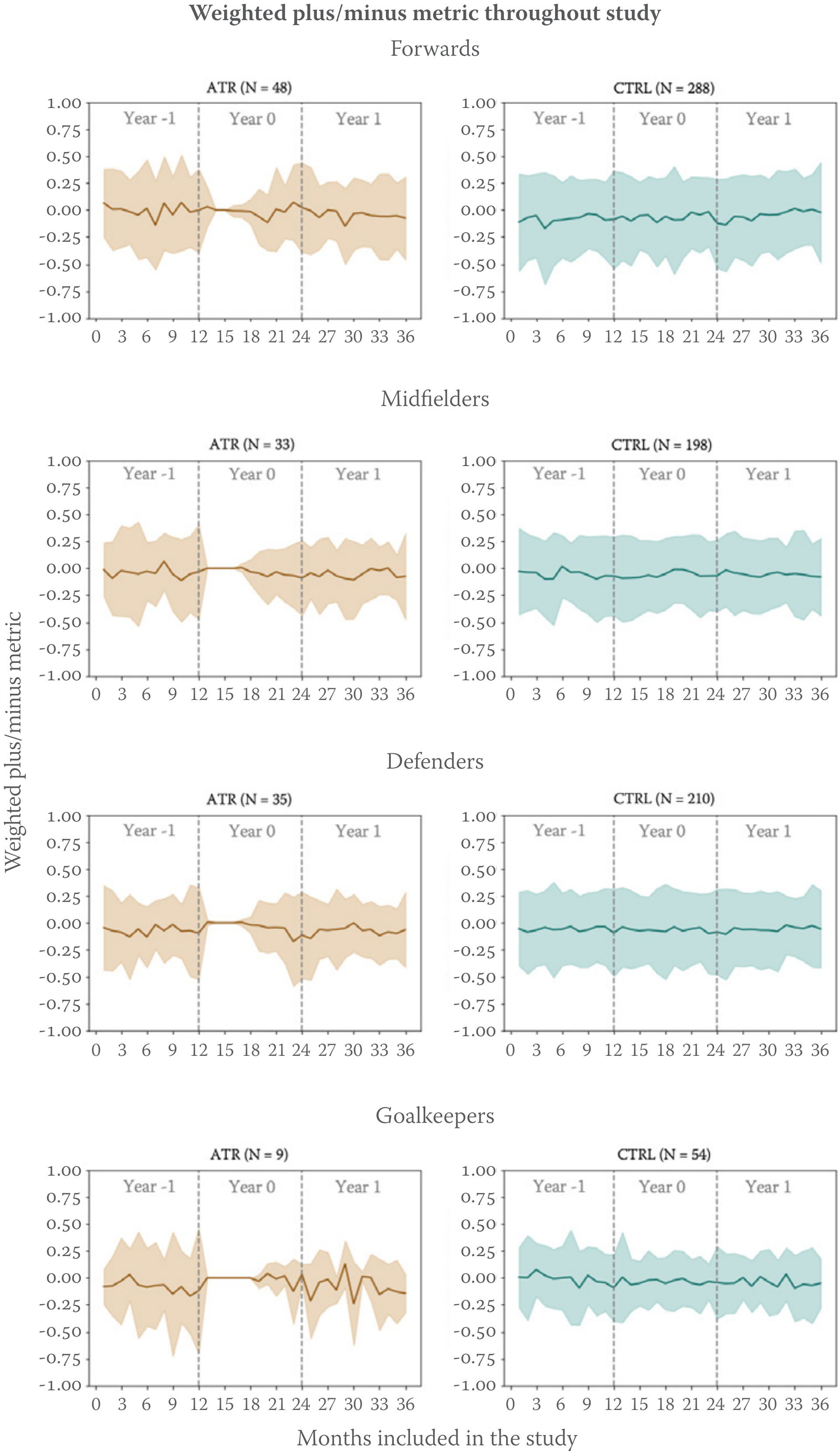

FIGURE 59 | Plot of the weighted plus/minus metric [29] (y-axis) for all players included throughout the study time frame and computed in 30-day intervals (x-axis) per group and playing position. Shaded areas correspond to standard deviation. ATR: Achilles tendon rupture group. CTRL: matched-control group.

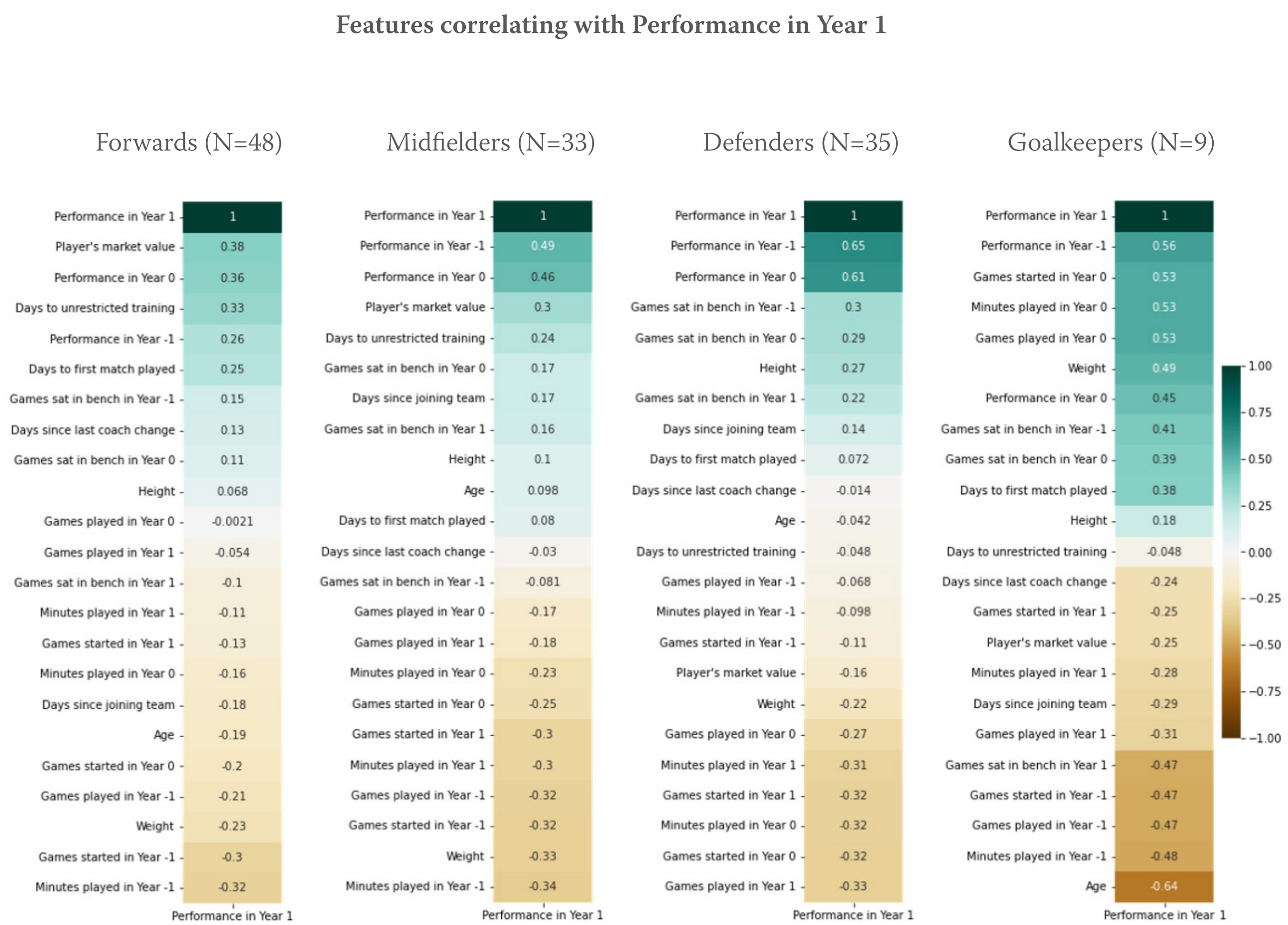

FIGURE 60 | Heatmap of statistical correlations between performance in Year 1 and other features for the Achilles tendon rupture group per playing position.

TABLE 33 | Comparison between the Achilles tendon rupture and matched-control groups regarding match performance

	YEAR -1			YEAR 0			YEAR 1		
	ATR	CTRL	p	ATR	CTRL	p	ATR	CTRL	p
Forwards	0.17 (2.72)	-0.18 (3.08)	n.s.	-0.11 (0.94)	-0.28 (2.42)	n.s.	-0.10 (1.40)	-0.05 (2.87)	n.s.
Midfielders	0.207 (3.51)	-0.24 (2.22)	n.s.	-0.17 (0.94)	-0.22 (2.64)	n.s.	-0.19 (1.59)	-0.14 (2.47)	n.s.
Defenders	-0.63 (2.23)	-0.24 (2.54)	n.s.	-0.22 (1.16)	-0.48 (2.77)	n.s.	-0.56 (1.66)	-0.34 (2.69	n.s.
Goalkeepers	0.18 (2.94)	0.0 (0.99)	n.s.	-0.14 (0.40)	-0.30 (1.79)	n.s.	-0.77 (1.42)	-0.15 (1.50)	n.s.

Comparison between the Achilles tendon rupture (ATR) and matched-control (CTRL) groups regarding match performance computed using the weighted plus/minus metric described by Schultze and Wellbrock [29]. Statistical significance set at $p < 0.05$. All values expressed as medians and interquartile ranges. n.s.: without statistical significance.

TABLE 34 | Statistical correlations between Performance in Year 1 and features with statistical significance

FEATURE	p	PEARSON'S R	95% CI
	FORWARDS (N = 48)		
Player's market value	0.007	0.38	0.10 to 0.60
Performance in Year 0	0.01	0.36	0.08 to 0.58
Days to unrestricted training	0.02	0.33	0.05 to 0.56
Minutes played in Year -1	0.03	-0.32	-0.56 to -0.04
Games started in Year -1	0.04	-0.3	-0.54 to -0.02
	MIDFIELDERS (N = 33)		
Performance in Year -1	0.004	0.49	0.18 to 0.71
Performance in Year 0	0.007	0.46	0.14 to 0.69
	DEFENDERS (N = 35)		
Performance in Year -1	< 0.001	0.65	0.40 to 0.81
Performance in Year 0	< 0.001	0.61	0.34 to 0.78
	GOALKEEPERS (N = 9)		
No features with statistically significant correlations			

Statistical correlations between Performance in Year 1, computed using the weighted plus/minus metric described by Schultze and Wellbrock [29], and other features, with statistical significance, for the Achilles tendon rupture group per playing position. Statistical significance set at $p < 0.05$.

DISCUSSION

The objective of the present study was to assess the effect of ATRs on individual player performance using a weighted PM metric, with the main finding being that no statistically significant differences were found between Year -1 and Year 1, despite a statistically significant decrease in the average MPM.

Previous studies comparing match participation before and after ATRs have shown contradictory results, with some reporting a statistically significant reduction in MPM [3, 33], while others have not [5, 31]. Of note, a post-injury decrease in minutes played has also been observed in basketball, as has games played in American football [20]. Differences between studies may be attributed to how match participation was calculated, and how matches and players were selected for inclusion, e.g., some studies may have only considered official matches while others may have also included friendly matches, or some studies may have found predominantly higher profile leagues and players through searches, typically with higher pre-injury performance and, consequently, with better post-injury match participation.

Pre-injury, i.e., Year -1, average MPMs were comparable between the ATR and CTRL groups, but not in Year 0 and Year 1, which provides confidence in the results of the present study. Although a slight downward trend was observed in the CTRL group, the negative effect of an ATR in match participation was evident. It can be hypothesized that, for some players, the long recovery time may act as a tipping point for loss of pitch time since the player will lose its place to another teammate. Soccer is a team sport, and when an athlete is injured, another athlete takes his or her place. The recovering player will have to outperform other players in the same position, who, by the time unrestricted practice is allowed again, have been training and competing regularly for a significant portion of the season.

Differences in the number of matches lost due to medical issues between the ATR and CTRL groups, and between Year -1 and Year 1 in the ATR group, were not statistically significant. Patients with previous ATRs exhibit increased knee loading during jumping and/or jogging [28, 36], increased knee range of motion and overextension of the knee on initial contact during running [16], and/or increased knee flexion and reduced hip extension [25]. It has been hypothesized that these changes in lower limb biomechanics, which are correlated with tendon elongation following an ATR [4], may put athletes at risk of knee injuries [18, 27]. However, because of the relatively low incidence of severe knee injuries, such as an anterior cruciate ligament tear [8], the present study may be underpowered to detect differences between the ATR and CTRL groups in the allotted time frame. Furthermore, due to limitations regarding detection of injuries of lesser severity [13], and inability to adequately adjust for exposure, smaller differences between groups may have been undetected.

Players suffering from ATRs exhibited return to similar levels of performance as measured by a weighted PM metric. Although PM metrics have been mainly used in sports analytics, e.g., in basketball and ice-hockey [17], their use in the assessment of return-to-performance following injury has also been reported [2, 34]. On the other hand, PM metrics have been criticized for being too simplistic and, thus, "adjusted" versions of these metrics have also been proposed, e.g., to account for the strengths of teammates, or whether the player is in the home or away team. The PM metric used herein, chosen for its applicability to the available data and straightforwardness, adjusts a player's contribution to team performance by accounting for the team's winning probabilities [29]. As noted elsewhere [17], while comparing two players with a PM metric of zero, one in the top performing team and the other in worst team in a league, the player in the worst team probably deserves more recognition. Accordingly, one notable limitation of PM metrics is related to their use in comparing players from different teams [15]. However, because the main objective of the present study was to measure performance throughout time for each player, using this kind of metric was justified.

Several factors correlating with performance in Year 1 were identified for the ATR group. Notably, in accordance with our previous report, pre-injury performance exhibited the strongest correlation performance in Year 1 for midfielders, defenders, and goalkeepers. For forwards, the pre-injury player's market value exhibited a stronger correlation, albeit this parameter may as well be considered a surrogate performance indicator. Also reinforcing our previous findings [3], the number of days elapsed between injury and return to unrestricted training and first match played were positively correlated with performance in Year 1, although only the former reached statistical significance and only for forwards. Besides a better recovery of a player's physical abilities, possible explanations for these findings include lesser fear of re-injury, and decreased kinesiophobia [19], which are probably required for high level performance. Athletes' concerns over reinjury are justified, as previous injury has been long recognized as significant risk factor for injury in elite football [11]. Of note, Bengtsson et al. reported a 13% decrease in the odds of suffering a muscle injury in the first match played after moderate or severe injuries (i.e., those with more than 8 days of absence) with each additional completed training session [1].

The main limitation of this study is related to the lack of ability to confirm the diagnosis, since data was gathered from a publicly available source and not from first-hand medical assessment. To account for this limitation, two researchers independently sought further evidence of the athlete sustaining an ATR, such as in club press reports and player interviews. Another important limitation is the relatively small sample size for some playing positions, which may have precluded certain correlations from reaching statistical significance. Finally, limitations of the weighted PM metric used herein should be recognized, as it may not be sensitive enough to individual performance variations in certain scenarios, e.g., if the remaining team can compensate for a momentarily underperforming player. In addition, coaches may prefer to reserve players returning from prolonged recoveries to match moments where the score is *settled*, i.e., when the match is felt to be either won or lost, which will not affect the weighted PM metric.

Implications for clinical practice and future research

The results of the present study may be used to inform athletes sustaining ATRs and help make career decisions. Despite a deleterious effect on match participation, players suffering these injuries were able to return to a comparable level of performance, as measured using a weighted PM metric. Athletes and staff need to be counseled about the possibility that previously recognized long-lasting consequences of ATRs on sports participation may reflect an "opportunity cost" related to the prolonged recovery time inherent to such an injury, and not necessarily loss of technical ability.

Further research may be aimed at evaluating the psychological consequences to athletes and common beliefs of athletes and staff regarding ATRs and their implications for future physical function in sports. Research directed at soccer performance indicators and changes induced by injuries are also of interest. Although several key performance indicators have been proposed for soccer analytics [12, 14], their feasibility as outcome measures in the context of medical research needs to be considered. Lastly, epidemiological studies on the incidence of future lower limb injuries following an ATR are also needed.

CONCLUSION

Athletes suffering from ATRs played at a similar performance level one-year post-injury, despite a decrease in match participation according to a weighted PM metric. A delayed return to unrestricted training was correlated with better performance in Year 1 for forwards.

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Section Zeta

Conclusion

Chapter 12: General discussion and future research

CHAPTER 12
General discussion and future research

GENERAL DISCUSSION

Despite widespread and continued research interest, Achilles tendon ruptures (ATRs) remain a challenging clinical problem [8, 15, 17]. This thesis focused on using computational models to guide the management of ATRs throughout the injury-recovery cycle, specifically *pre-injury*, *pre-treatment,* and *post-treatment,* with four main objectives:

> **1.** Develop and validate a finite element model of the aponeurotic and free Achilles tendon (AT) and use the model to evaluate the influence of tendon length on the predicted rupture load and tear progression at different severities of partial ruptures.
>
> **2.** Evaluate if there was evidence that Achilles tendon elongation was a relevant problem; if so, assess which repair technique reduced this risk the most.
>
> **3.** Evaluate the clinical outcomes of endoscopic flexor hallucis longus (FHL) transfers for acute ruptures and perform an early cost-effectiveness analysis.
>
> **4.** Assess how match participation evolves after an ATR in elite soccer players, whether the level of match participation can be predicted, and which factors are most important for prediction.

A summary of the research projects conducted and their key findings and relevance are presented in the following sections.

Objective 1

Chapter 3 presents a finite element model of the Achilles tendon, which included both the aponeurotic and free portion regions, developed and validated using experimental data found in the literature. To our knowledge, this was the first model that featured both the aponeurotic and free tendon regions while also allowing subtendon sliding. It was noted that the model was most sensitive to changes in the material model's fiber dispersion parameter, which is interesting because the loss of collagen fiber orientation is a hallmark of tendinopathy [9].

In **Chapter 4**, this model was then used to study whether the length of the free tendon region influenced the results of a simulated rupture. To this end, additional models were developed using free-form deformation, and several sensitivity analyses were conducted. It was found that free tendon length does not seem to influence the results of an *in silico* rupture experiment significantly. Of note, increased free tendon length is commonly found in tendinopathic Achilles tendons [3], but from the results of this experiment, it can be inferred that this increased length is most probably a consequence and not a causal factor. Additionally, it was noted that the model was highly sensitive to variations in the subtendons' cross-section area (CSA). Although the high sensitivity of models to AT CSA variations has been previously noted in other finite element analysis models [18, 19], this interplay between the soleus and gastrocnemius subtendons' CSA as a possible risk factor for injury is a novel finding.

Despite its common use [6], the "50% rule" for conservative versus surgical treatment of partial tendon ruptures lacks substantial experimental evidence. Thus, considering that variations in CSA greatly influenced the mechanical behavior of the model, **Chapter 5** presents a study in which it was hypothesized that partial ruptures, even if with less than 50% of the mediolateral tendon diameter, exhibit a significant risk of tear progression with an early loading rehabilitation protocol. Several models were developed, considering small, moderate, and extreme degrees of sub-tendon twisting [4], which is especially relevant considering that a 50% rupture in a patient with moderate or extreme twisting of the subtendons will signify that one of the subtendons is (almost) fully transected. Loads simulating the initial stages of rehabilitation were used for the simulations [1, 2, 10], and the rupture criteria used in the previous study were also used in the present study. The experiments were run using healthy and tendinopathic tendon material properties. In addition, a model with a geometry simulating a tendinopathic tendon was also developed as part of a sensitivity analysis based on experimental data [14]. It was found that ruptures affecting less than 50% of the tendon may cause tear progression with loads comparable to walking with a Walker boot and a heel raise, regardless of material properties and tendon geometry. Considering the long-term impairments associated with ATRs and that its conservative treatment carries an increased risk of re-rupture [13], and that outcomes are worse in the long-term in case of complications such as re-ruptures [20], the "50% rule" should be reconsidered, particularly in cases of existing significant tendon degeneration or high-demand patients.

Objective 2

In **Chapter 6**, a systematic review first assessed whether resulting tendon elongation from ATRs was a significant problem. Only studies that included analysis of statistical correlations between post-rupture tendon elongation, or tendon length, and clinical, strength, or biomechanical outcomes were included. Evidence was not found supporting the hypothesis that tendon elongation affects clinical and strength outcomes in the general population. However, fair evidence of the deleterious effect of tendon elongation on biomechanical parameters was found. Of note, the elicited changes in biomechanical parameters may increase the risk of further lower limb injuries [12, 16] or negatively affect performance. In addition, it should be noted that evidence of tendon elongation affecting strength not being found may be related to measurement problems since some of these deficits were only apparent when examining specific parts of the ankle range of motion [7].

Since tendon elongation was considered a relevant problem, **Chapter 7** presents an additional systematic review to evaluate which repair technique would provide the least risk of tendon elongation. To this end, a systematic review and network meta-analysis (NMA) of biomechanical cadaveric studies was conducted. In this study, both failure loads and elongation with cyclic loading were evaluated. It was found that repairs augmented with scaffolds provide the largest resistance to failure, but the repair with the highest likelihood of providing the least elongation with cyclic loading was a modified triple-Kessler stitch [2]. Interestingly, there was no correlation between rankings from the failure load and elongation with cyclic loading NMAs. In addition, it was noted that current rehabilitation protocols elicit loads [1, 2, 11] that may exceed the loading capacity of existing surgical repair techniques and materials.

Objective 3

In **Chapter 8**, a prospective clinical study, which to our knowledge, was the first in patients with acute injuries, carried out to evaluate the clinical results of an endoscopic FHL transfer for acute ATRs is presented. This study featured 50 participants with a minimum follow-up of 18 months. The FHL tendon was transferred, and no direct work on the AT was performed. In the follow-up magnetic resonance imaging (MRI) evaluations, the FHL was found to be adjacent to the AT, with the latter exhibiting good signs of healing and no edema. Patients did not perceive strength deficits in the first metatarsophalangeal joint. One patient sustained a re-rupture, treated conservatively, as the transferred FHL was intact. With this study, an endoscopic FHL transfer, previously advocated in treating chronic ATRs or re-ruptures [2, 8, 14], was also recognized as a viable alternative in the acute setting.

Chapter 9 presents an early analysis conducted to assess endoscopic FHL transfers' cost-effectiveness profile. Early analyses allow the assessment of the potential economic benefits of new or emerging therapies and which factors may most determine the outcomes [5]. In this study, an endoscopic FHL transfer was compared with conservative treatment, open surgery, and minimally invasive surgery. In addition, one-way and probabilistic sensitivity analyses were conducted. It was found that, compared to current treatments, endoscopic FHL transfers exhibit a promising cost-effectiveness profile and that improvements regarding treatment benefits are more likely to render a new treatment cost-effective, which highlights the importance of providing favorable patient outcomes while avoiding complications with long-lasting effects.

Objective 4

Chapter 10 presents a study using a semi-automated data extraction method to retrieve match participation data of elite soccer players suffering from ATRs. This study used publicly available data, and two researchers manually confirmed all ruptures independently using cross-referencing with other sources. Data from 209 players and more than 32,000 matches were used, constituting the largest published series. It was found that most players will improve match participation, measured as average minutes played per match (MPM), during the first year post-injury, with goalkeepers still improving at two years. Approximately 50% of players exhibited a decrease in match participation following the injury compared with the year before. A weak positive correlation was found between the time until the first match played and the average MPM between one and two years following injury. A machine learning (ML) classifier was trained to assess whether predicting which players would return to a similar or improved level of match participation would be possible. Good performance of the ML classifier was attained with an AUROC of 0.81. Interestingly, pre-injury performance was most important for predicting the level of match participation, signaling that player context at the time of injury is a determinant factor for post-rupture match participation.

Chapter 11 presents a study in which the individual performance of athletes with ATRs was compared to a control group using a plus/minus (PM) metric. The control group was created by matching players regarding position, age, height, and league affiliation. The study analyzed matches played, matches as a starter, average and cumulative MPM, and individual player performance using a weighted PM metric. Statistically significant differences were found between athletes that sustained ATRs and the control group in the time frame between one and two years after injury (Year 1) but not in the preceding year (Year -1) regarding average MPM. However, there were no significant differences in the net weighted PM metric per player position between Year -1 and Year 1 in either or between the groups, which suggests that athletes with ATRs performed at a similar level one year after the injury, despite a decrease in match participation, according to the PM metric, signifying that this decrease in match participation may reflect factors other than the potential loss of technical abilities.

Future research

Based on the findings from this thesis, areas that could be considered for future research include:

1. Computational modeling: the finite element model presented herein could be improved by developing methods to simulate different regional material properties, such as areas of marked tendinopathy or previous injury. In addition, free-form deformation could be used to generate personalized models, which could then be used to explore the biomechanics of various rehabilitation protocols and optimize the recovery process considering the patient's tendon material properties.

2. Tendon elongation: The effects of tendon elongation on clinical outcomes deserve further evaluation, as a threshold value to consider that AT elongation is *problematic* has yet to be defined. Furthermore, the influence of post-rupture AT elongation on future lower limb injuries should be clarified.

3. Repair techniques: Minimally invasive repair techniques are commonly used due to their lower incidence of severe wound healing complications than open repair techniques. However, their resistance to elongation with cyclic loading does not match that of a modified triple-Kessler stitch, an open technique. Therefore, future research should be aimed at developing minimally invasive techniques that provide increased resistance to tendon elongation.

4. Endoscopic FHL transfers: Given the promising early results of this treatment, further research should investigate the long-term outcomes and cost-effectiveness of endoscopic FHL transfers.

5. Impact of ATRs on match participation and athlete performance: Strategies to improve return-to-play and post-injury match participation could be the subject of future research. In addition, assessing factors affecting return-to-play, including psychological and team-related factors, is of interest.

6. Machine learning applications: Building large datasets from publicly available information to train machine learning algorithms is promising. However, further model validation and other potential uses should be investigated. For instance, similar models could be developed to predict ATR risk in athletes or optimize rehabilitation protocols.

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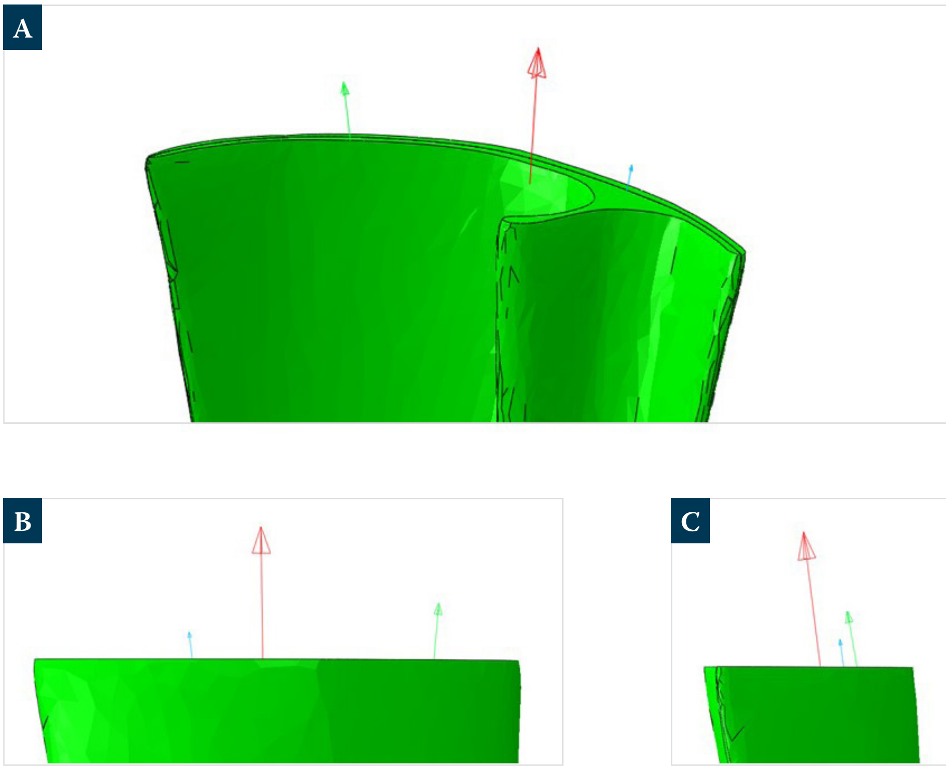
Appendix

APPENDIX I
Supplementary material for Chapter 3

MATERIAL AND METHODS

FIGURE I-A | VISUAL REPRESENTATION OF FORCES ACTING ON THE PROXIMAL END OF THE MODEL
A: Anterosuperior view.
B: Posterior view.
C: Side view. Red arrow: Soleus load. Green arrow: medial gastrocnemius load. Blue arrow: lateral gastrocnemius load.
Arrow size is proportional to force magnitude.



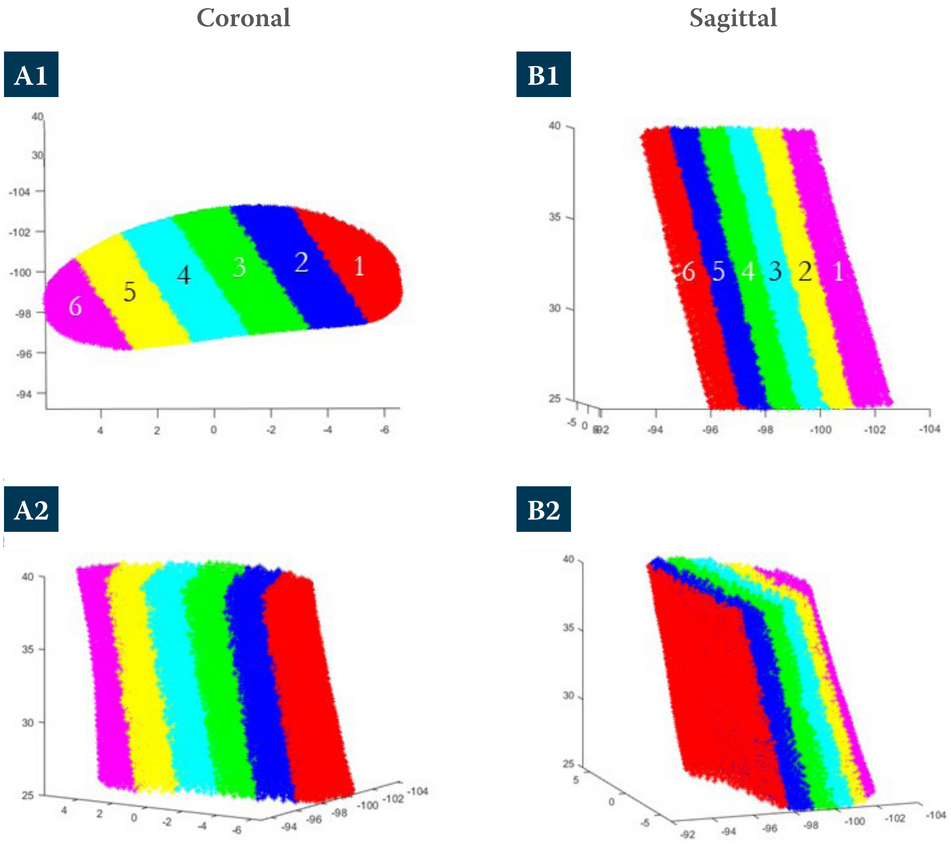


FIGURE I-B | PLANES IN THE EVALUATION OF CORONAL AND SAGITTAL NODAL DISPLACEMENTS
Planes in the evaluation of coronal and sagittal nodal displacements. Section numbers correspond to those represented in Figure 6. A1: Superior view of coronal plane sections. A2: Anterolateral view of coronal plane sections. B1: Lateral view of sagittal plane sections. B2: Anterolateral view of sagittal plane sections.

Creation of additional models with different subtendon twist

Two additional models of the subtendon twist variations described by Edama et al.[1] were created and are shown in Figure C.

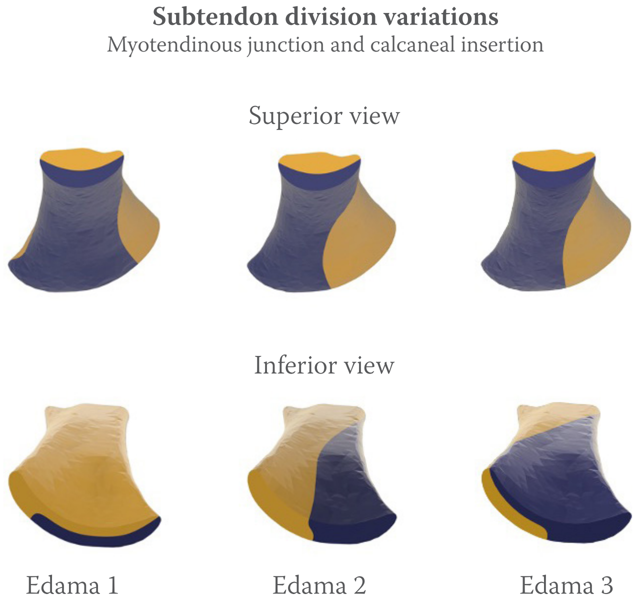


FIGURE I-C | ADDITIONAL MODELS OF SUBTENDON TWIST
Different models of subtendon twist according to the descriptions of Edama et al. Edama 1 corresponds to the Type 1 (Least twisting, found in 50% of specimens), Edama 2 to the Type 2 (Moderate twisting, found in 43% of specimens) and Edama 3 to the Type 3 (Extreme twisting, found in 7% of specimens).

RESULTS

Additional models of subtendon twist

Modeling conditions were similar for these models (subtendon sliding modelled using anisotropic friction). Overall, the results of these additional models, shown in Figures D to J, were similar to the baseline model (Edama 2, Moderate twisting). In the Edama 3 (Extreme twisting model), results slightly deviated from the validation range, particularly for transverse plane rotation and sagittal plane displacements, which can be attributed to the relatively low prevalence of this variation (7% in the study by Edama et al.).[1]

Results of model validation for the two additional models regarding subtendon twisting compared to the baseline anisotropic friction model. SDs: Standard deviations. CSA: cross-sectional area. MLD: mediolateral diameter. APD: anteroposterior diameter. TPR: transverse plane rotation.

FIGURE I-D | EVALUATION OF ADDITIONAL SUBTENDON TWIST MODELS (CSA)

Target mean and SDs

Edama 1

Edama 2

Edama 3

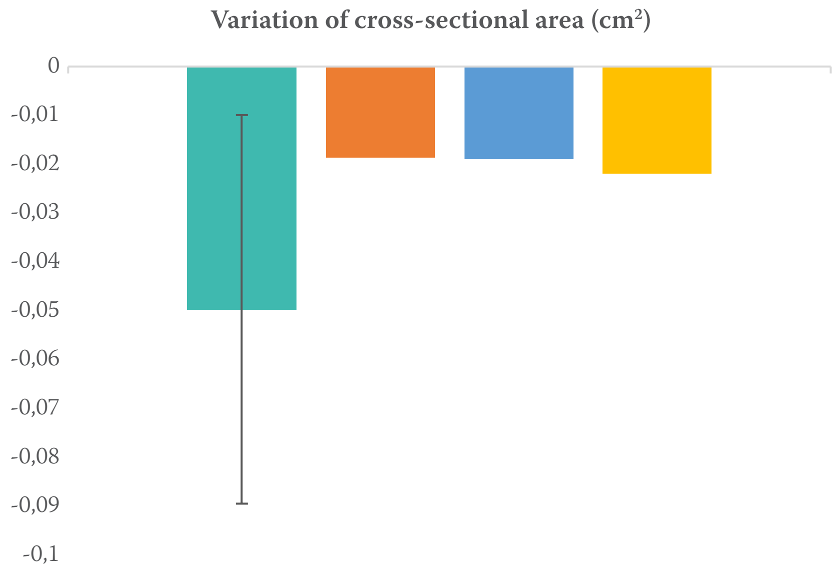


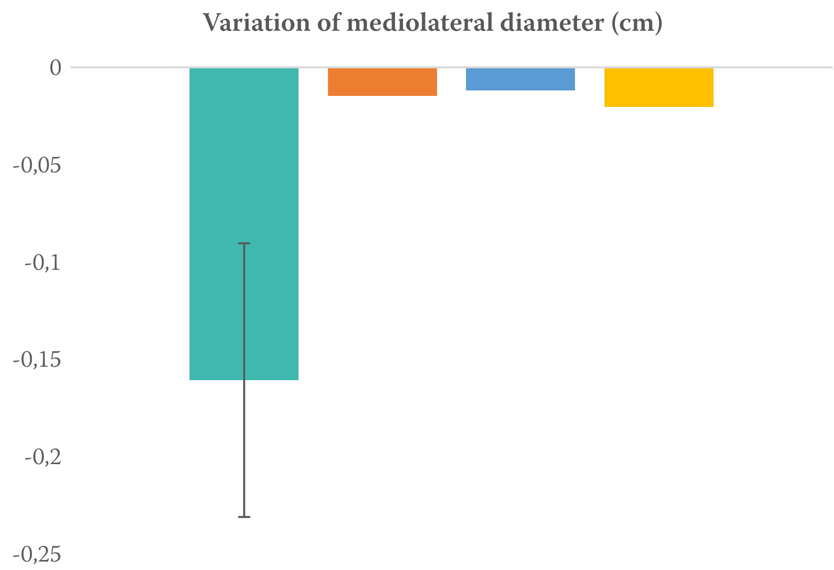
FIGURE I-E | EVALUATION OF ADDITIONAL SUBTENDON TWIST MODELS (MLD)

Target mean and SDs

Edama 1

Edama 2

Edama 3



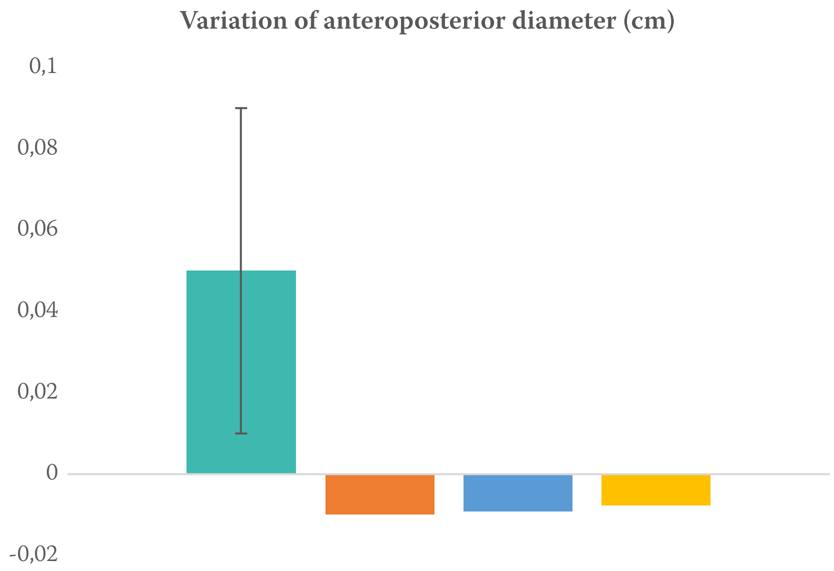


FIGURE I-F | EVALUATION OF ADDITIONAL SUBTENDON TWIST MODELS (APD)

- Target mean and SDs
- Edama 1
- Edama 2
- Edama 3

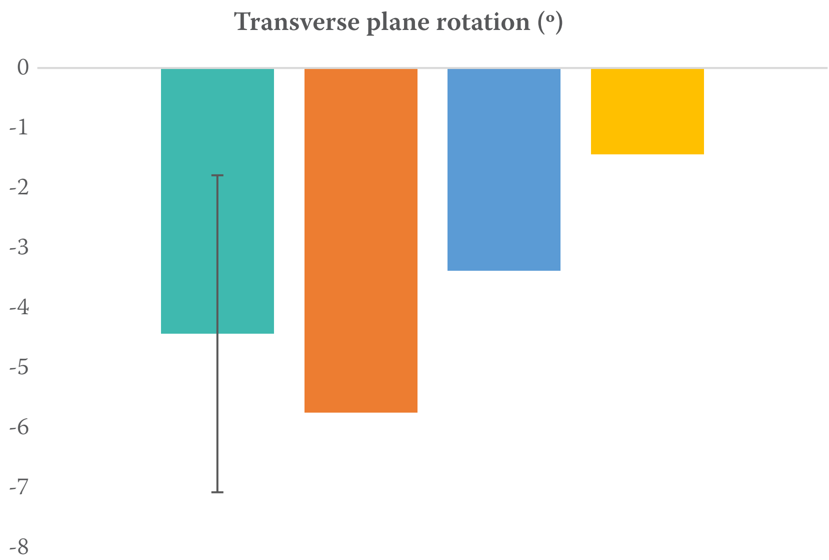


FIGURE I-G | EVALUATION OF ADDITIONAL SUBTENDON TWIST MODELS (TPR)

- Target mean and SDs
- Edama 1
- Edama 2
- Edama 3

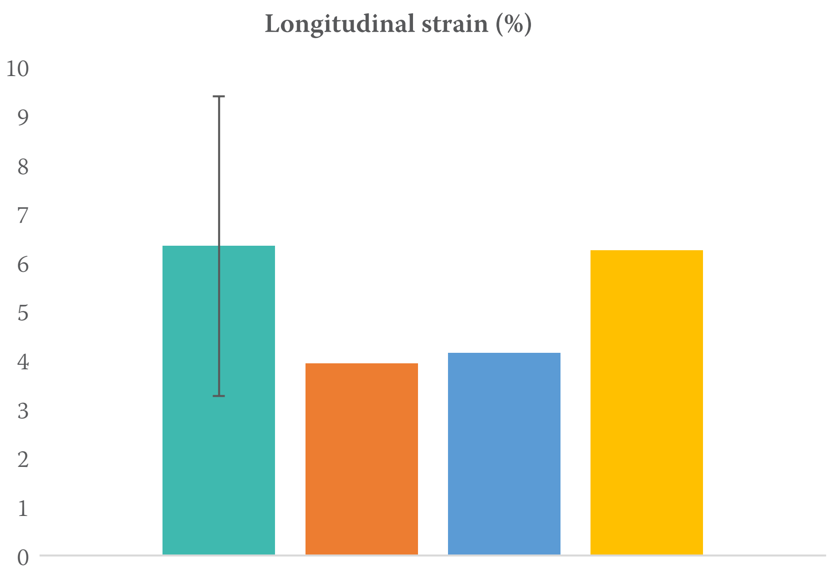


FIGURE I-H | EVALUATION OF ADDITIONAL SUBTENDON TWIST MODELS (LONGITUDINAL STRAIN)

- Target mean and SDs
- Edama 1
- Edama 2
- Edama 3

FIGURE I-I | EVALUATION OF ADDITIONAL SUBTENDON TWIST MODELS (SAGITTAL DISPLACEMENTS)

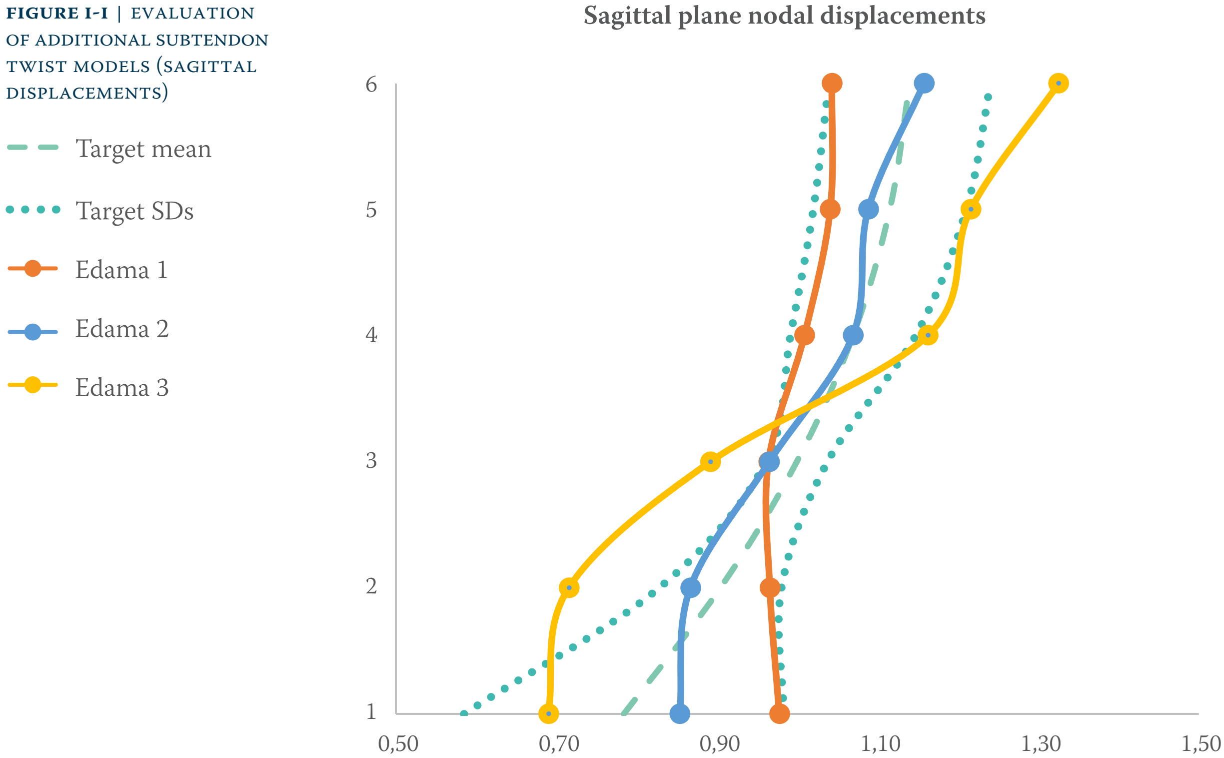
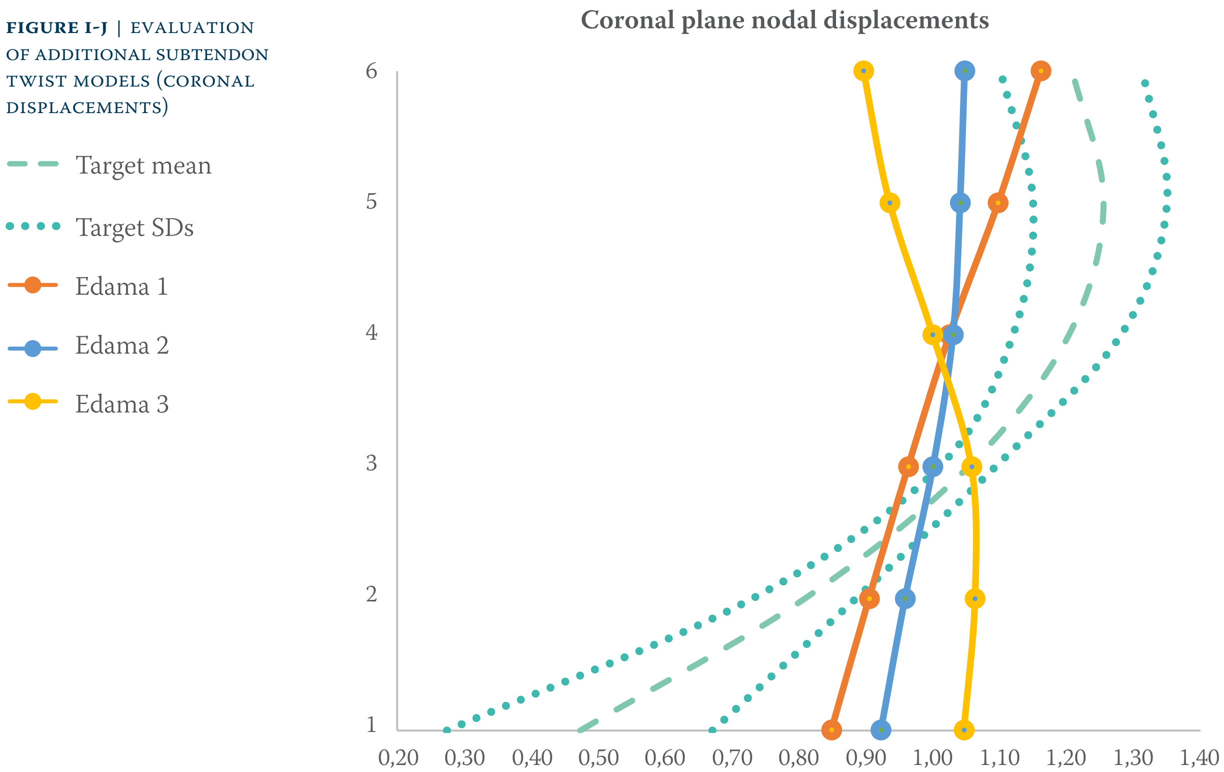


FIGURE I-J | EVALUATION OF ADDITIONAL SUBTENDON TWIST MODELS (CORONAL DISPLACEMENTS)



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APPENDIX II
Supplementary material for Chapter 7

TABLE II-A | FULL-TEXT PAPERS EXCLUDED, WITH REASONS

AUTHORS	TITLE	JOURNAL	YEAR	REASON FOR EXCLUSION
Hockenbury and Johns	A biomechanical in vitro comparison of open versus percutaneous repair of tendon Achilles.	Foot & Ankle	1990	No failure load or gap testing reported
Cretnik et al.	The strength of percutaneous methods of repair of the Achilles tendon: a biomechanical study	Medicine and Science in Sports And Exercise	2000	Compared technique modification
Turgut A et al.	Endoscopy, assisted percutaneous repair of the Achilles tendon ruptures: a cadaveric and clinical study.	Knee Surgery, Sports Traumatology, Arthroscopy	2002	No failure load or gap testing reported
Lewis et al.	Strength analysis and comparison of the Teno Fix Tendon Repair System with the two-strand modified Kessler repair in the Achilles tendon.	Foot & ankle international	2003	Load not reported
Labib et al.	The effect of ankle position on the static tension in the Achilles tendon before and after operative repair: a biomechanical cadaver study.	Foot & Ankle International	2007	Only one technique was tested; no comparative data available
Shepard et al.	Biomechanical testing of epitenon suture strength in Achilles tendon repairs.	Foot & Ankle International	2007	Only compared epitendinous augmentations
Lee et al.	Optimizing Achilles tendon repair: effect of epitendinous suture augmentation on the strength of Achilles tendon repairs.	Foot & Ankle International	2008	Only compared epitendinous augmentations
Shepard et al	Biomechanical comparison of the simple running and cross-stitch epitenon sutures in Achilles tendon repairs.	Foot & Ankle International	2008	Only compared epitendinous augmentations
Chan et al.	Endoscopic-assisted repair of acute Achilles tendon rupture with Krackow suture: an anatomic study.	Foot And Ankle Surgery	2009	No failure load or gap testing reported

Continuation of table II-A

AUTHORS	TITLE	JOURNAL	YEAR	REASON FOR EXCLUSION
Labib et al.	The "Giftbox" repair of the Achilles tendon: a modification of the Krackow technique.	Foot & Ankle International	2009	Compared technique modification
Hong et al.	Core Weave Versus Krackow Technique for Achilles Tendon Repair: A Biomechanical Study	Foot & Ankle International	2010	Only one end sutured
Cook et al.	Strength of braided polyblend polyethylene sutures versus braided polyester sutures in Achilles tendon repair: a cadaveric study.	Journal Of The American Podiatric Medical Association	2010	Only compared suture materials
El-Shazly et al.	Endoscopic Achilles tendon augmentation with a graft loop anatomic and radiologic study.	Foot And Ankle Surgery	2011	No failure load or gap testing reported
Sadoghi et al.	Initial Achilles tendon repair strength-synthesized biomechanical data from 196 cadaver repairs	International Orthopaedics	2012	Systematic review
Zhao et al.	Application of Different Biomaterials in Achilles Tendon Repair for Exercise Injury	Advanced Research On Material Science, Environment Science And Computer Science	2014	Review
Kanz et al.	Biomechanical evaluation of a knotless barbed suture repair in a human Achilles tendon rupture model.	Foot & Ankle Specialist	2014	Only compared suture materials
Gnandt et al.	High-Tensile Strength Tape Versus High-Tensile Strength Suture: A Biomechanical Study.	Arthroscopy	2016	Mixed specimens of different anatomical locations
Makulavicius et al.	Comparative anatomical study of standard percutaneous and modified medialized percutaneous Bunnell type repair for artificial Achilles tendon rupture: positive effect of medialization of the stitches with lower risk of sural nerve injury	Folia Morphologica	2016	No failure load or gap testing reported
De la Fuente et al.	Clinical failure after Dresden repair of mid-substance Achilles tendon rupture: human cadaveric testing.	Knee Surgery, Sports Traumatology, Arthroscopy	2017	No failure load reported

Continuation of table II-A

AUTHORS	TITLE	JOURNAL	YEAR	REASON FOR EXCLUSION
Yammine et al.	Efficacy of repair techniques of the Achilles tendon: A meta-analysis of human cadaveric biomechanical studies.	Foot	2017	Systematic review
Mait et al.	A biomechanical comparison of different tendon repair techniques	Foot And Ankle Surgery	2017	Conference abstract
Frunz et al.	Biomechanical Comparison of Suture Material (PDS CTX vs MonoMax) for Achilles Tendon Reconstruction (Adelaide Suture-double strand cross locked suture-technique)	Swiss Medical Weekly	2017	Conference poster; not enough data
Backus et al.	Effect of Suture Caliber and Number of Core Strands on Repair of Acute Achilles Ruptures: A Biomechanical Study.	Foot & Ankle International	2017	Compared only different combinations of sutures
Wagner et al.	Proximal and Distal Failure Site Analysis in Percutaneous Achilles Tendon Rupture Repair	Foot & Ankle International	2019	Only one end sutured
THE FOLLOWING PAPERS WERE EXCLUDED AFTER QUALITATIVE EVALUATION				
Mortensen et al.	Achilles tendon repair: a new method of Achilles tendon repair tested on cadaverous materials.	The Journal of Trauma	1991	Not randomized
Watson et al.	The strength of Achilles tendon repair: an in vitro study of the biomechanical behavior in human cadaver tendons.	Foot & Ankle International	1995	Not randomized
Zandbergen et al.	Surgical treatment of Achilles tendon rupture: examination of strength of 3 types of suture techniques in a cadaver model.	Acta Orthopaedica	2005	Not randomized
Giza et al.	Augmented Tendon Achilles Repair Using a Tissue Reinforcement Scaffold: A Biomechanical Study	Foot & Ankle International	2011	Not randomized
Manent et al.	Assessment of the Resistance of Several Suture Techniques in Human Cadaver Achilles Tendons.	The Journal of Foot and Ankle Surgery	2017	Not randomized
Lee et al.	A biomechanical comparison of different tendon repair techniques	Foot and Ankle Surgery	2017	Not randomized
Yang et al.	The biomechanical study of rupture of Achilles Tendon and repair by different suture techniques.	Pakistan Journal of Medical Sciences	2018	Insufficient description of the procedure

TABLE II-B | RISK OF BIAS IN INDIVIDUAL STUDIES

STUDY	SELECTION	PREPARATION	DESCRIPTION	LOADING	STATISTICS	OVERALL
COMPARISONS OF SUTURE TECHNIQUES						
Frosch et al. (2020)	High	Low	Low	Low	Low	Low
Nguyen et al. (2020)	Medium	Medium	Low	Low	Medium	Medium
Cottom et al. (2017)	High	Low	Low	Medium	Medium	Medium
Van Dyke et al. (2017)	Medium	Low	Low	Low	High	Medium
Clanton et al. (2015)	Medium	Medium	Low	Low	Low	Low
Demetracopoulos et al. (2014)	Medium	Low	Low	Low	Medium	Low
Heitman et al. (2011)	Medium	Low	Low	Medium	Low	Medium
McCoy et al. (2010)	High	Medium	Low	Low	High	High
Herbort et al. (2008)	Low	Low	Low	Medium	Medium	Medium
Huffard et al. (2008)	Low	Low	Low	Medium	Low	Low
Jaakkola et al. (2000)	Low	Medium	Low	Medium	High	Medium
COMPARISONS WITH AUGMENTATION PROCEDURES						
Berlet et al. (2014)	Low	Low	Low	Low	High	Low
Wisbeck et al. (2012)	Medium	Low	Low	Medium	Low	Medium
Magnussen et al. (2011)	Low	Medium	Low	Low	Medium	Low
Barber et al. (2008)	Medium	Medium	Low	Medium	Medium	Medium
Gebauer et al. (2007)	Medium	Low	Low	Low	Medium	Low

TABLE II-C | LEAGUE TABLE FOR FAILURE LOAD NETWORK META-ANALYSIS

Achillon	.	.	.	.	.	31.64 (-23.05 to 86.33)	.	.
-119.86 (-299.97 to 60.25)	Bunnell	-35.00 (-133.99 to 63.99)	.	.	.	.	84.14 (39.39 to 128.90)	80.00 (7.84 to 152.16)
-169.86 (-373.51 to 33.79)	-50.00 (-145.05 to 45.05)	Bunnell + Plantaris	.	.	.	.	146.00 (49.68 to 242.32)	115.00 (14.85 to 215.15)
-32.60 (-226.24 to 161.05)	87.26 (16.13 to 158.39)	137.26 (28.38 to 246.15)	DLKS	.	.	.	-3.12 (-58.41 to 52.17)	.
35.64 (-46.77 to 118.05)	155.50 (-42.57 to 353.57)	205.50 (-14.19 to 425.19)	68.24 (-142.22 to 278.69)	Double Bunnell	29.00 (-40.69 to 98.69)	-4.00 (-65.64 to 57.64)	.	.
64.64 (-19.43 to 148.71)	184.50 (-14.26 to 383.26)	234.50 (14.18 to 454.82)	97.24 (-113.87 to 308.34)	29.00 (-40.69 to 98.69)	Double Kessler	-33.00 (-96.85 to 30.85)	.	.
31.64 (-23.05 to 86.33)	151.50 (-36.73 to 339.73)	201.50 (-9.36 to 412.37)	64.24 (-136.99 to 265.46)	-4.00 (-65.64 to 57.64)	-33.00 (-96.85 to 30.85)	Double Krackow	.	.
-35.72 (-221.30 to 149.87)	84.14 (39.39 to 128.90)	134.14 (40.34 to 227.95)	-3.12 (-58.41 to 52.17)	-71.36 (-274.42 to 131.70)	-100.36 (-304.10 to 103.38)	-67.36 (-260.83 to 126.12)	Kessler	-31.00 (-99.45 to 37.45)
-54.86 (-246.91 to 137.19)	65.00 (-1.65 to 131.65)	115.00 (14.85 to 215.15)	-22.26 (-107.50 to 62.97)	-90.50 (-299.48 to 118.48)	-119.50 (-329.14 to 90.14)	-86.50 (-286.18 to 113.18)	-19.14 (-84.01 to 45.72)	Kessler + Plantaris
-162.86 (-316.00 to -9.72)	-43.00 (-137.81 to 51.81)	7.00 (-127.25 to 141.25)	-130.26 (-248.79 to -11.74)	-198.50 (-372.40 to -24.60)	-227.50 (-402.19 to -52.80)	-194.50 (-357.11 to -31.89)	-127.14 (-231.98 to -22.30)	-108.00 (-223.89 to 7.89)
-546.06 (-765.64 to -326.48)	-426.2 (-609.92 to -242.48)	-376.20 (-583.05 to -169.35)	-513.46 (-710.48 to -316.45)	-581.70 (-816.24 to -347.16)	-610.70 (-845.83 to -375.57)	-577.70 (-803.99 to -351.41)	-510.34 (-699.44 to -321.25)	-491.20 (-686.64 to -295.76)
-401.16 (-572.51 to -229.81)	-281.30 (-403.36 to -159.24)	-231.30 (-386.00 to -76.60)	-368.56 (-509.84 to -227.29)	-436.80 (-626.94 to -246.66)	-465.80 (-656.66 to -274.94)	-432.80 (-612.67 to -252.93)	-365.44 (-495.45 to -235.44)	-346.30 (-485.37 to -207.23)
-457.26 (-625.66 to -288.86)	-337.40 (-455.29 to -219.51)	-287.40 (-438.83 to -135.97)	-424.66 (-562.35 to -286.98)	-492.90 (-680.39 to -305.41)	-521.90 (-710.12 to -333.68)	-488.90 (-665.96 to -311.84)	-421.54 (-547.64 to -295.45)	-402.40 (-537.82 to -266.97)
-591.86 (-772.72 to -411.00)	-472.00 (-607.09 to -336.91)	-422.00 (-587.17 to -256.83)	-559.26 (-711.93 to -406.59)	-627.50 (-826.25 to -428.75)	-656.50 (-855.94 to -457.05)	-623.50 (-812.45 to -434.55)	-556.14 (-698.45 to -413.84)	-537.00 (-687.63 to -386.37)
-269.84 (-450.70 to -88.98)	-149.98 (-285.07 to -14.89)	-99.98 (-265.15 to 65.19)	-237.24 (-389.91 to -84.58)	-305.48 (-504.23 to -106.73)	-334.48 (-533.92 to -135.04)	-301.48 (-490.43 to -112.53)	-234.12 (-376.43 to -91.82)	-214.98 (-365.61 to -64.35)
-85.40 (-213.75 to 42.95)	34.46 (-91.89 to 160.81)	84.46 (-73.65 to 242.57)	-52.80 (-197.80 to 92.20)	-121.04 (-273.57 to 31.49)	-150.04 (-303.47 to 3.39)	-117.04 (-256.56 to 22.48)	-49.68 (-183.73 to 84.36)	-30.54 (-173.40 to 112.32)
-264.91 (-418.62 to -111.20)	-145.05 (-287.23 to -2.87)	-95.05 (-266.07 to 75.97)	-232.31 (-391.29 to -73.34)	-300.55 (-474.96 to -126.14)	-329.55 (-504.75 to -154.35)	-296.55 (-459.70 to -133.40)	-229.19 (-378.25 to -80.14)	-210.05 (-367.07 to -53.02)
-260.36 (-346.88 to -173.84)	-140.50 (-340.31 to 59.31)	-90.50 (-311.77 to 130.77)	-227.76 (-439.86 to -15.67)	-296.00 (-387.07 to -204.93)	-325.00 (-417.58 to -232.42)	-292.00 (-359.04 to -224.96)	-224.64 (-429.41 to -19.88)	-205.50 (-416.14 to 5.14)

Square matrix of all available pairwise comparisons, showing mean differences (N) and 95% confidence intervals. Lower left corner represents indirect comparisons and upper right corner available direct comparisons. Table should be read from left to right.

Continuation of table II-C

.	.	.	.	.	.	-85.40 (-213.75 to 42.95)	.	.
-43.00 (-137.81 to 51.81)	.	.	.	.	.	.	.	.
.	.	.	.	.	.	.	.	.
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.	.	.	.	.	.	.	.	.
.	.	.	.	.	.	.	.	-292.00 (-359.04 to -224.96)
.	.	.	.	.	.	.	.	.
.	.	.	.	.	.	.	.	.
Krackow	-383.20 (-540.57 to -225.83)	-238.30 (-315.18 to -161.42)	-294.40 (-364.47 to -224.33)	-429.00 (-525.23 to -332.77)	-106.98 (-203.21 to -10.75)	77.46 (-6.07 to 160.99)	-102.05 (-208.00 to 3.90)	.
-383.20 (-540.57 to -225.83)	Krackow + Cnx	.	.	.	.	.	.	.
-238.30 (-315.18 to -161.42)	144.90 (-30.25 to 320.05)	Krackow + GrJ	.	.	.	.	.	.
-294.40 (-364.47 to -224.33)	88.80 (-83.47 to 261.07)	-56.10 (-160.12 to 47.92)	Krackow + TCR	.	.	.	.	.
-429.00 (-525.23 to -332.77)	-45.80 (-230.26 to 138.66)	-190.70 (-313.87 to -67.53)	-134.60 (-253.63 to -15.57)	Krackow + TM	.	.	.	.
-106.98 (-203.21 to -10.75)	276.22 (91.76 to 460.68)	131.32 (8.16 to 254.48)	187.42 (68.39 to 306.45)	322.02 (185.93 to 458.11)	MFSS	.	.	.
77.46 (-6.07 to 160.99)	460.66 (282.49 to 638.83)	315.76 (202.24 to 429.28)	371.86 (262.83 to 480.89)	506.46 (379.04 to 633.88)	184.44 (57.02 to 311.86)	PARS	-179.51 (-264.09 to -94.93)	.
-102.05 (-208.00 to 3.90)	281.15 (91.43 to 470.87)	136.25 (5.35 to 267.15)	192.35 (65.32 to 319.38)	326.95 (183.82 to 470.08)	4.93 (-138.20 to 148.06)	-179.51 (-264.09 to -94.93)	PARS Mid-substance	.
-97.50 (-273.39 to 78.39)	285.70 (49.69 to 521.71)	140.80 (-51.16 to 332.75)	196.90 (7.57 to 386.23)	331.50 (131.01 to 531.99)	9.48 (-191.01 to 209.97)	-174.96 (-329.75 to -20.17)	4.55 (-171.84 to 180.94)	Triple bundle

Mean difference > 1 favors the technique in the upper left cell. Blank cells represent unavailable comparisonsKessler or Bunnell + Plantaris: augmentation of the repair with a plantaris tendon. Krackow + [biomaterial]: techniques in which the Krackow repair was augmented with a biomaterial; Cnx: Conexa; GrJ: GraftJacket; TCR: Trellis Collagen Ribbon; TM: TissueMend Soft Tissue Repair Matrix. DLKS: double loop knot stitch; MFSS: multifilament stainless steel; PARS: Percutaneous Achilles Repair System; PARS Midsubstance: augmentation of the PARS technique with suture anchors.

TABLE II-D | LEAGUE TABLE FOR ELONGATION AFTER CYCLIC LOADING NETWORK META-ANALYSIS

Achillon	.	.	.	.	.	.	.	.	-2.30 (-5.67 to 1.07)	-0.10 (-3.20 to 3.00)	4.70 (2.80 to 6.60)
-4.18 (-7.11 to -1.24)	Bunnell	.	0.38 (-1.10 to 1.86)	-1.30 (-2.02 to -0.58)	.	.	.	.	.	.	.
-4.08 (-7.55 to -0.60)	0.10 (-1.76 to 1.96)	DLKS	0.28 (-0.85 to 1.41)	.	.	.	.	.	.	.	.
-3.80 (-7.08 to -0.51)	0.38 (-1.10 to 1.86)	0.28 (-0.85 to 1.41)	Kessler	.	.	.	.	.	.	.	.
-5.48 (-8.32 to -2.63)	-1.30 (-2.02 to -0.58)	-1.40 (-3.40 to 0.60)	-1.68 (-3.33 to -0.03)	Krackow	2.50 (0.47 to 4.53)	3.90 (1.44 to 6.36)	2.50 (1.42 to 3.58)	1.94 (0.11 to 3.77)	3.71 (3.03 to 4.39)	4.72 (2.68 to 6.76)	.
-2.98 (-6.47 to 0.52)	1.20 (-0.95 to 3.35)	1.10 (-1.75 to 3.95)	0.82 (-1.79 to 3.43)	2.50 (0.47 to 4.53)	Krackow + GrJ	.	.	.	.	.	.
-1.58 (-5.33 to 2.18)	2.60 (0.04 to 5.16)	2.50 (-0.67 to 5.67)	2.22 (-0.74 to 5.18)	3.90 (1.44 to 6.36)	1.40 (-1.78 to 4.58)	Krackow + TCR	.	.	.	.	.
-2.98 (-6.02 to 0.07)	1.20 (-0.10 to 2.50)	1.10 (-1.17 to 3.37)	0.82 (-1.15 to 2.79)	2.50 (1.42 to 3.58)	-0.00 (-2.30 to 2.30)	-1.40 (-4.08 to 1.28)	Krackow + TM	.	.	.	.
-3.54 (-6.92 to -0.15)	0.64 (-1.33 to 2.61)	0.54 (-2.17 to 3.25)	0.26 (-2.20 to 2.72)	1.94 (0.11 to 3.77)	-0.56 (-3.29 to 2.17)	-1.96 (-5.02 to 1.10)	-0.56 (-2.69 to 1.57)	MFSS	.	.	.
-1.77 (-4.54 to 1.00)	2.41 (1.41 to 3.40)	2.31 (0.20 to 4.42)	2.03 (0.24 to 3.81)	3.71 (3.03 to 4.39)	1.21 (-0.93 to 3.34)	-0.19 (-2.74 to 2.35)	1.21 (-0.07 to 2.48)	1.77 (-0.19 to 3.72)	PARS	1.25 (-0.49 to 2.99)	7.00 (4.04 to 9.96)
-0.52 (-3.22 to 2.19)	3.66 (1.68 to 5.64)	3.56 (0.84 to 6.28)	3.28 (0.81 to 5.75)	4.96 (3.12 to 6.80)	2.46 (-0.28 to 5.20)	1.06 (-2.01 to 4.13)	2.46 (0.32 to 4.60)	3.02 (0.42 to 5.62)	1.25 (-0.49 to 2.99)	PARS Midsubs-tance	4.80 (2.15 to 7.45)
4.70 (2.80 to 6.60)	8.88 (6.42 to 11.33)	8.78 (5.69 to 11.86)	8.50 (5.63 to 11.36)	10.18 (7.83 to 12.52)	7.68 (4.57 to 10.78)	6.28 (2.88 to 9.67)	7.68 (5.09 to 10.26)	8.24 (5.26 to 11.21)	6.47 (4.21 to 8.73)	5.22 (3.04 to 7.39)	Triple Kessler

Square matrix of all available pairwise comparisons, showing mean differences (mm) and confidence intervals. Lower left corner represents indirect comparisons and upper right corner available direct comparisons. Table should be read from left to right. Mean difference < 1 favors the technique in the upper left cell. Blank cells represent unavailable comparisons. Krackow + [biomaterial]: techniques in which the Krackow repair was augmented with a biomaterial; GrJ: GraftJacket; TCR: Trellis Collagen Ribbon; TM: TissueMend Soft Tissue Repair Matrix. DLKS. Double loop knot stitch; MFSS: multifilament stainless steel; PARS: Percutaneous Achilles Repair System; PARS Midsubstance: augmentation of the PARS technique with suture anchors.

TABLE II-E | RESULTS OF SUBGROUP SENSITIVITY ANALYSIS

EXCLUSION OF STUDIES WITHOUT MATCHED PAIRS					
FAILURE LOAD			ELONGATION AFTER CYCLIC LOADING		
Subnetwork 1			1	Krackow + TCR	0.9131
1	Krackow + TM	0.9624	2	Krackow + TM	0.7051
2	Krackow + Cnx	0.8909	3	Krackow + GrJ	0.6731
3	Krackow + TCR	0.7581	4	MFSS	0.5292
4	Krackow + GrJ	0.6378	5	Kessler	0.4746
5	MFSS	0.4994	6	DLKS	0.3678
6	Krackow	0.3555	7	Bunnell	0.3177
7	Bunnell	0.2687	8	Krackow	0.0194
8	Kessler	0.0782			
9	DLKS	0.0489			
Subnetwork 2					
1	Triple bundle	1.0000			
2	Achillon	0.4461			
3	Double Krackow	0.0539			

EXCLUSION OF STUDIES WITH CADAVERS AGED MORE THAN 70 YEARS OLD					
FAILURE LOAD			ELONGATION AFTER CYCLIC LOADING		
1	Krackow + TM	0.9997	1	Triple Kessler	1.0000
2	Krackow + TCR	0.8814	2	Achillon	0.7514
3	Krackow + GrJ	0.7848	3	PARS Midsubstance	0.7107
4	PARS Midsubstance	0.6657	4	Krackow + TCR	0.5236
5	Krackow	0.5546	5	PARS	0.4940
6	PARS	0.4322	6	Krackow + GrJ	0.2725
7	Achillon	0.3297	7	Krackow + TM	0.2465
8	Double Krackow	0.1797	8	Krackow	0.0013
9	Double Bunnell	0.1523			
10	Double Kessler	0.0199			

Ranking of techniques according to subgroup sensitivity analysis using the *netrank* function in *netmeta*. A higher P-score represents the likelihood of a given technique ranking first in comparison with other techniques. In the load-to-failure network meta-analysis, two subnetworks remained after exclusion of studies with unmatched pairs. Kessler or Bunnell + Plantaris: augmentation of the repair with a plantaris tendon. Krackow + [biomaterial]: techniques in which the Krackow repair was augmented with a biomaterial; Cnx: Conexa; GrJ: GraftJacket; TCR: Trellis Collagen Ribbon; TM: TissueMend Soft Tissue Repair Matrix. DLKS: double loop knot stitch; MFSS: multifilament stainless steel. PARS: Percutaneous Achilles Repair System; PARS Midsubstance: augmentation of the PARS technique with suture anchors.

TABLE II-F | RESULTS OF SENSITIVITY ANALYSIS, "GIFTBOX" KRACKOW IN DIFFERENT NODE

P-SCORE					
FAILURE LOAD			ELONGATION AFTER CYCLIC LOADING		
Subnetwork 1			*Subnetwork 1*		
1	Krackow + TM	0.9740	1	Triple Kessler	1.0000
2	Krackow + Cnx	0.9258	2	Achillon	0.7799
3	Krackow + TCR	0.7558	3	PARS Midsubstance	0.7455
4	Krackow + GrJ	0.8231	4	Krackow + TCR	0.5701
5	MFSS	0.5882	5	PARS	0.5525
6	PARS Midsubstance	0.5811	6	Krackow + GrJ	0.3205
7	Triple bundle	0.5767	7	Krackow + TM	0.3028
8	Krackow	0.4242	8	MFSS	0.2254
9	PARS	0.3194	9	Krackow	0.0035
10	Achillon	0.2325	*Subnetwork 2*		
11	Double Krackow	0.1351	1	Kessler	0.7855
12	Double Bunnell	0.1242	2	DLKS	0.5901
13	Double Kessler	0.0270	3	Bunnell	0.5884
Subnetwork 2			4	"Giftbox" Krackow	0.0359
1	Bunnell + Plantaris	0.8706			
2	"Giftbox" Krackow	0.8399			
3	Bunnell + Plantaris	0.6612			
4	Kessler + Plantaris	0.2958			
5	Kessler	0.1693			
6	DLKS	0.1632			

Ranking of techniques according to sensitivity analysis, "Giftbox" Krackow in different node, using the *netrank* function in *netmeta*. A higher P-score represents the likelihood of a given technique ranking first in comparison with other techniques. Kessler or Bunnell + Plantaris: augmentation of the repair with a plantaris tendon. Krackow + [biomaterial]: techniques in which the Krackow repair was augmented with a biomaterial; Cnx: Conexa; GrJ: GraftJacket; TCR: Trellis Collagen Ribbon; TM: TissueMend Soft Tissue Repair Matrix. DLKS: double loop knot stitch; "Giftbox" Krackow: 4-strand Krackow repair modification; MFSS: multifilament stainless steel; PARS: Percutaneous Achilles Repair System; PARS Midsubstance: augmentation of the PARS technique with suture anchors.

TABLE II-G | CINeMA report for the failure load network meta-analysis

COMPARISON	NUMBER OF STUDIES	WITHIN-STUDY BIAS	REPORTING BIAS	INDIRECTNESS	IMPRECISION	HETEROGENEITY	INCOHERENCE	CONFIDENCE RATING
Achillon:Double Krackow	2	Some concerns	Undetected	No concerns	Some concerns	Some concerns	No concerns	Moderate
Achillon:PARS	1	No concerns	Undetected	No concerns	Major concerns	No concerns	No concerns	Moderate
Bunnell:Bunnell + Plantaris	1	No concerns	Undetected	No concerns	Major concerns	No concerns	No concerns	Low
Bunnell:Kessler	2	No concerns	Undetected	No concerns	No concerns	Major concerns	No concerns	Moderate
Bunnell:Kessler + Plantaris	1	No concerns	Undetected	No concerns	Some concerns	Some concerns	No concerns	Moderate
Bunnell:Krackow	1	Some concerns	Undetected	No concerns	Major concerns	No concerns	No concerns	Moderate
Bunnell + Plantaris:Kessler	1	No concerns	Undetected	No concerns	No concerns	Major concerns	No concerns	Low
Bunnell + Plantaris:Kessler + Plantaris	1	No concerns	Undetected	No concerns	No concerns	Major concerns	No concerns	Moderate
DLKS:Kessler	1	No concerns	Undetected	No concerns	Major concerns	No concerns	No concerns	Low
Double Bunnell:Double Kessler	1	Major concerns	Undetected	No concerns	Major concerns	No concerns	No concerns	Low
Double Bunnell:Double Krackow	1	Major concerns	Undetected	No concerns	Major concerns	No concerns	No concerns	Low
Double Kessler:Double Krackow	1	Major concerns	Undetected	No concerns	Some concerns	Some concerns	No concerns	Low
Double Krackow:Triple bundle	1	Some concerns	Undetected	No concerns	No concerns	Major concerns	No concerns	Low
Kessler:Kessler + Plantaris	1	No concerns	Undetected	No concerns	Major concerns	No concerns	No concerns	Low
Krackow:Krackow + Cnx	1	Some concerns	Undetected	No concerns	No concerns	Major concerns	No concerns	Low
Krackow:Krackow + GrJ	1	Some concerns	Undetected	No concerns	No concerns	Major concerns	No concerns	Low
Krackow:Krackow + TCR	1	No concerns	Undetected	No concerns	No concerns	Major concerns	No concerns	Moderate
Krackow:Krackow + TM	1	No concerns	Undetected	No concerns	No concerns	Major concerns	No concerns	Moderate
Krackow:MFSS	1	Some concerns	Undetected	No concerns	No concerns	Major concerns	No concerns	Low

Continuation of table II-G

COMPARISON	NUMBER OF STUDIES	WITHIN-STUDY BIAS	REPORTING BIAS	INDIRECTNESS	IMPRECISION	HETEROGENEITY	INCOHERENCE	CONFIDENCE RATING
Krackow:PARS	1	Some concerns	Undetected	No concerns	Some concerns	Some concerns	No concerns	Moderate
Krackow:PARS Midsubstance	1	Some concerns	Undetected	No concerns	Some concerns	Some concerns	No concerns	Moderate
PARS:PARS Midsubstance	1	Some concerns	Undetected	No concerns	No concerns	Major concerns	No concerns	Low
Achillon:Bunnell	0	Some concerns	Undetected	No concerns	Major concerns	No concerns	No concerns	Low
Achillon:Bunnell + Plantaris	0	Some concerns	Undetected	No concerns	Some concerns	Some concerns	No concerns	Low
Achillon:DLKS	0	No concerns	Undetected	No concerns	Major concerns	No concerns	No concerns	Low
Achillon:Double Bunnell	0	Some concerns	Undetected	No concerns	Major concerns	No concerns	No concerns	Low
Achillon:Double Kessler	0	Some concerns	Undetected	No concerns	Some concerns	Some concerns	No concerns	Low
Achillon:Kessler	0	Some concerns	Undetected	No concerns	Major concerns	No concerns	No concerns	Low
Achillon:Kessler + Plantaris	0	Some concerns	Undetected	No concerns	Major concerns	No concerns	No concerns	Low
Achillon:Krackow	0	Some concerns	Undetected	No concerns	No concerns	Major concerns	No concerns	Low
Achillon:Krackow + Cnx	0	Some concerns	Undetected	No concerns	No concerns	Major concerns	No concerns	Low
Achillon:Krackow + GrJ	0	Some concerns	Undetected	No concerns	No concerns	Major concerns	No concerns	Low
Achillon:Krackow + TCR	0	No concerns	Undetected	No concerns	No concerns	Major concerns	No concerns	Moderate
Achillon:Krackow + TM	0	No concerns	Undetected	No concerns	No concerns	Major concerns	No concerns	Moderate
Achillon:MFSS	0	Some concerns	Undetected	No concerns	No concerns	Major concerns	No concerns	Low
Achillon:PARS Midsubstance	0	Some concerns	Undetected	No concerns	No concerns	Major concerns	No concerns	Low
Achillon:Triple bundle	0	Some concerns	Undetected	No concerns	No concerns	Major concerns	No concerns	Low
Bunnell:DLKS	0	No concerns	Undetected	No concerns	No concerns	Major concerns	No concerns	Low
Bunnell:Double Bunnell	0	Some concerns	Undetected	No concerns	Major concerns	No concerns	No concerns	Low

Continuation of table II-G

COMPARISON	NUMBER OF STUDIES	WITHIN-STUDY BIAS	REPORTING BIAS	INDIRECTNESS	IMPRECISION	HETEROGENEITY	INCOHERENCE	CONFIDENCE RATING
Bunnell:Double Kessler	0	Some concerns	Undetected	No concerns	Some concerns	Some concerns	No concerns	Low
Bunnell:Double Krackow	0	Some concerns	Undetected	No concerns	Major concerns	No concerns	No concerns	Low
Bunnell:Krackow + Cnx	0	Some concerns	Undetected	No concerns	No concerns	Major concerns	No concerns	Low
Bunnell:Krackow + GrJ	0	Some concerns	Undetected	No concerns	No concerns	Major concerns	No concerns	Low
Bunnell:Krackow + TCR	0	Some concerns	Undetected	No concerns	No concerns	Major concerns	No concerns	Low
Bunnell:Krackow + TM	0	Some concerns	Undetected	No concerns	No concerns	Major concerns	No concerns	Low
Bunnell:MFSS	0	Some concerns	Undetected	No concerns	No concerns	Major concerns	No concerns	Low
Bunnell:PARS	0	Some concerns	Undetected	No concerns	Major concerns	No concerns	No concerns	Low
Bunnell:PARS Midsubstance	0	Some concerns	Undetected	No concerns	No concerns	Major concerns	No concerns	Low
Bunnell:Triple bundle	0	Some concerns	Undetected	No concerns	Major concerns	No concerns	No concerns	Low
Bunnell + Plantaris:DLKS	0	No concerns	Undetected	No concerns	No concerns	Major concerns	No concerns	Low
Bunnell + Plantaris:Double Bunnell	0	Some concerns	Undetected	No concerns	Some concerns	Some concerns	No concerns	Low
Bunnell + Plantaris:Double Kessler	0	Some concerns	Undetected	No concerns	No concerns	Major concerns	No concerns	Low
Bunnell + Plantaris:Double Krackow	0	Some concerns	Undetected	No concerns	Some concerns	Some concerns	No concerns	Low
Bunnell + Plantaris:Krackow	0	No concerns	Undetected	No concerns	Major concerns	No concerns	No concerns	Moderate
Bunnell + Plantaris:Krackow + Cnx	0	Some concerns	Undetected	No concerns	No concerns	Major concerns	No concerns	Low
Bunnell + Plantaris:Krackow + GrJ	0	Some concerns	Undetected	No concerns	No concerns	Major concerns	No concerns	Low
Bunnell + Plantaris:Krackow + TCR	0	No concerns	Undetected	No concerns	No concerns	Major concerns	No concerns	Moderate
Bunnell + Plantaris:Krackow + TM	0	No concerns	Undetected	No concerns	No concerns	Major concerns	No concerns	Moderate
Bunnell + Plantaris:MFSS	0	Some concerns	Undetected	No concerns	Major concerns	No concerns	No concerns	Moderate
Bunnell + Plantaris:PARS	0	Some concerns	Undetected	No concerns	Major concerns	No concerns	No concerns	Low

Continuation of table II-G

COMPARISON	NUMBER OF STUDIES	WITHIN-STUDY BIAS	REPORTING BIAS	INDIRECTNESS	IMPRECISION	HETEROGENEITY	INCOHERENCE	CONFIDENCE RATING
Bunnell + Plantaris:PARS Midsubs-tance	0	Some concerns	Undetected	No concerns	Major concerns	No concerns	No concerns	Moderate
Bunnell + Plantaris:Triple bundle	0	Some concerns	Undetected	No concerns	Major concerns	No concerns	No concerns	Low
DLKS:Double Bunnell	0	Some concerns	Undetected	No concerns	Major concerns	No concerns	No concerns	Low
DLKS:Double Kessler	0	Some concerns	Undetected	No concerns	Major concerns	No concerns	No concerns	Low
DLKS:Double Krackow	0	Some concerns	Undetected	No concerns	Major concerns	No concerns	No concerns	Low
DLKS:Kessler + Plantaris	0	No concerns	Undetected	No concerns	Major concerns	No concerns	No concerns	Low
DLKS:Krackow	0	No concerns	Undetected	No concerns	No concerns	Major concerns	No concerns	Low
DLKS:Krackow + Cnx	0	Some concerns	Undetected	No concerns	No concerns	Major concerns	No concerns	Low
DLKS:Krackow + GrJ	0	Some concerns	Undetected	No concerns	No concerns	Major concerns	No concerns	Low
DLKS:Krackow + TCR	0	No concerns	Undetected	No concerns	No concerns	Major concerns	No concerns	Low
DLKS:Krackow + TM	0	No concerns	Undetected	No concerns	No concerns	Major concerns	No concerns	Low
DLKS:MFSS	0	Some concerns	Undetected	No concerns	No concerns	Major concerns	No concerns	Low
DLKS:PARS	0	Some concerns	Undetected	No concerns	Major concerns	No concerns	No concerns	Low
DLKS:PARS Midsubstance	0	Some concerns	Undetected	No concerns	No concerns	Major concerns	No concerns	Low
DLKS:Triple bundle	0	Some concerns	Undetected	No concerns	No concerns	Major concerns	No concerns	Low
Double Bunnell:Kessler	0	Some concerns	Undetected	No concerns	Major concerns	No concerns	No concerns	Low
Double Bunnell:Kessler + Plantaris	0	Some concerns	Undetected	No concerns	Major concerns	No concerns	No concerns	Low
Double Bunnell:Krackow	0	Some concerns	Undetected	No concerns	No concerns	Major concerns	No concerns	Low
Double Bunnell:Krackow + Cnx	0	Some concerns	Undetected	No concerns	No concerns	Major concerns	No concerns	Low
Double Bunnell:Krackow + GrJ	0	Some concerns	Undetected	No concerns	No concerns	Major concerns	No concerns	Low

Continuation of table II-G

COMPARISON	NUMBER OF STUDIES	WITHIN-STUDY BIAS	REPORTING BIAS	INDIRECTNESS	IMPRECISION	HETEROGENEITY	INCOHERENCE	CONFIDENCE RATING
Double Bunnell:Krackow + TCR	0	Some concerns	Undetected	No concerns	No concerns	Major concerns	No concerns	Low
Double Bunnell:Krackow + TM	0	Some concerns	Undetected	No concerns	No concerns	Major concerns	No concerns	Low
Double Bunnell:MFSS	0	Some concerns	Undetected	No concerns	No concerns	Major concerns	No concerns	Low
Double Bunnell:PARS	0	Some concerns	Undetected	No concerns	Some concerns	Some concerns	No concerns	Low
Double Bunnell:PARS Midsubstance	0	Some concerns	Undetected	No concerns	No concerns	Major concerns	No concerns	Low
Double Bunnell:Triple bundle	0	Major concerns	Undetected	No concerns	No concerns	Major concerns	No concerns	Low
Double Kessler:Kessler	0	Some concerns	Undetected	No concerns	Major concerns	No concerns	No concerns	Low
Double Kessler:Kessler + Plantaris	0	Some concerns	Undetected	No concerns	Major concerns	No concerns	No concerns	Low
Double Kessler:Krackow	0	Some concerns	Undetected	No concerns	No concerns	Major concerns	No concerns	Low
Double Kessler:Krackow + Cnx	0	Some concerns	Undetected	No concerns	No concerns	Major concerns	No concerns	Low
Double Kessler:Krackow + GrJ	0	Some concerns	Undetected	No concerns	No concerns	Major concerns	No concerns	Low
Double Kessler:Krackow + TCR	0	Some concerns	Undetected	No concerns	No concerns	Major concerns	No concerns	Low
Double Kessler:Krackow + TM	0	Some concerns	Undetected	No concerns	No concerns	Major concerns	No concerns	Low
Double Kessler:MFSS	0	Some concerns	Undetected	No concerns	No concerns	Major concerns	No concerns	Low
Double Kessler:PARS	0	Some concerns	Undetected	No concerns	Some concerns	Some concerns	No concerns	Moderate
Double Kessler:PARS Midsubstance	0	Some concerns	Undetected	No concerns	No concerns	Major concerns	No concerns	Low
Double Kessler:Triple bundle	0	Major concerns	Undetected	No concerns	No concerns	Major concerns	No concerns	Low
Double Krackow:Kessler	0	Some concerns	Undetected	No concerns	Major concerns	No concerns	No concerns	Low
Double Krackow:Kessler + Plantaris	0	Some concerns	Undetected	No concerns	Major concerns	No concerns	No concerns	Low
Double Krackow:Krackow	0	Some concerns	Undetected	No concerns	No concerns	Major concerns	No concerns	Low
Double Krackow:Krackow + Cnx	0	Some concerns	Undetected	No concerns	No concerns	Major concerns	No concerns	Low

Continuation of table II-G

COMPARISON	NUMBER OF STUDIES	WITHIN-STUDY BIAS	REPORTING BIAS	INDIRECTNESS	IMPRECISION	HETEROGENEITY	INCOHERENCE	CONFIDENCE RATING
Double Krackow:Krackow + GrJ	0	Some concerns	Undetected	No concerns	No concerns	Major concerns	No concerns	Low
Double Krackow:Krackow + TCR	0	No concerns	Undetected	No concerns	No concerns	Major concerns	No concerns	Moderate
Double Krackow:Krackow + TM	0	No concerns	Undetected	No concerns	No concerns	Major concerns	No concerns	Moderate
Double Krackow:MFSS	0	Some concerns	Undetected	No concerns	No concerns	Major concerns	No concerns	Low
Double Krackow:PARS	0	No concerns	Undetected	No concerns	Some concerns	Some concerns	No concerns	Moderate
Double Krackow:PARS Midsubstance	0	Some concerns	Undetected	No concerns	No concerns	Major concerns	No concerns	Low
Kessler:Krackow	0	Some concerns	Undetected	No concerns	No concerns	Major concerns	No concerns	Low
Kessler:Krackow + Cnx	0	Some concerns	Undetected	No concerns	No concerns	Major concerns	No concerns	Low
Kessler:Krackow + GrJ	0	Some concerns	Undetected	No concerns	No concerns	Major concerns	No concerns	Low
Kessler:Krackow + TCR	0	No concerns	Undetected	No concerns	No concerns	Major concerns	No concerns	Moderate
Kessler:Krackow + TM	0	No concerns	Undetected	No concerns	No concerns	Major concerns	No concerns	Moderate
Kessler:MFSS	0	Some concerns	Undetected	No concerns	No concerns	Major concerns	No concerns	Low
Kessler:PARS	0	Some concerns	Undetected	No concerns	Major concerns	No concerns	No concerns	Low
Kessler:PARS Midsubstance	0	Some concerns	Undetected	No concerns	No concerns	Major concerns	No concerns	Low
Kessler:Triple bundle	0	Some concerns	Undetected	No concerns	No concerns	Major concerns	No concerns	Low
Kessler + Plantaris:Krackow	0	No concerns	Undetected	No concerns	Some concerns	Some concerns	No concerns	Moderate
Kessler + Plantaris:Krackow + Cnx	0	Some concerns	Undetected	No concerns	No concerns	Major concerns	No concerns	Low
Kessler + Plantaris:Krackow + GrJ	0	Some concerns	Undetected	No concerns	No concerns	Major concerns	No concerns	Low
Kessler + Plantaris:Krackow + TCR	0	No concerns	Undetected	No concerns	No concerns	Major concerns	No concerns	Moderate
Kessler + Plantaris:Krackow + TM	0	No concerns	Undetected	No concerns	No concerns	Major concerns	No concerns	Moderate
Kessler + Plantaris:MFSS	0	Some concerns	Undetected	No concerns	No concerns	Major concerns	No concerns	Low

Continuation of table II-G

COMPARISON	NUMBER OF STUDIES	WITHIN-STUDY BIAS	REPORTING BIAS	INDIRECTNESS	IMPRECISION	HETEROGENEITY	INCOHERENCE	CONFIDENCE RATING
Kessler + Plantaris:PARS	0	Some concerns	Undetected	No concerns	Major concerns	No concerns	No concerns	Low
Kessler + Plantaris:PARS Midsubs-tance	0	Some concerns	Undetected	No concerns	No concerns	Major concerns	No concerns	Low
Kessler + Plantaris:Triple bundle	0	Some concerns	Undetected	No concerns	Some concerns	Some concerns	No concerns	Low
Krackow:Triple bundle	0	Some concerns	Undetected	No concerns	Major concerns	No concerns	No concerns	Low
Krackow + Cnx:Krackow + GrJ	0	Some concerns	Undetected	No concerns	Some concerns	Some concerns	No concerns	Moderate
Krackow + Cnx:Krackow + TCR	0	Some concerns	Undetected	No concerns	Major concerns	No concerns	No concerns	Low
Krackow + Cnx:Krackow + TM	0	Some concerns	Undetected	No concerns	Major concerns	No concerns	No concerns	Low
Krackow + Cnx:MFSS	0	Some concerns	Undetected	No concerns	No concerns	Major concerns	No concerns	Low
Krackow + Cnx:PARS	0	Some concerns	Undetected	No concerns	No concerns	Major concerns	No concerns	Low
Krackow + Cnx:PARS Midsubstance	0	Some concerns	Undetected	No concerns	No concerns	Major concerns	No concerns	Low
Krackow + Cnx:Triple bundle	0	Some concerns	Undetected	No concerns	No concerns	Major concerns	No concerns	Low
Krackow + GrJ:Krackow + TCR	0	Some concerns	Undetected	No concerns	Major concerns	No concerns	No concerns	Low
Krackow + GrJ:Krackow + TM	0	Some concerns	Undetected	No concerns	No concerns	Major concerns	No concerns	Low
Krackow + GrJ:MFSS	0	Some concerns	Undetected	No concerns	No concerns	Major concerns	No concerns	Low
Krackow + GrJ:PARS	0	Some concerns	Undetected	No concerns	No concerns	Major concerns	No concerns	Low
Krackow + GrJ:PARS Midsubstance	0	Some concerns	Undetected	No concerns	No concerns	Major concerns	No concerns	Low
Krackow + GrJ:Triple bundle	0	Some concerns	Undetected	No concerns	Major concerns	No concerns	No concerns	Low
Krackow + TCR:Krackow + TM	0	No concerns	Undetected	No concerns	No concerns	Major concerns	No concerns	Moderate
Krackow + TCR:MFSS	0	Some concerns	Undetected	No concerns	No concerns	Major concerns	No concerns	Low
Krackow + TCR:PARS	0	Some concerns	Undetected	No concerns	No concerns	Major concerns	No concerns	Low

Continuation of table II-G

COMPARISON	NUMBER OF STUDIES	WITHIN-STUDY BIAS	REPORTING BIAS	INDIRECTNESS	IMPRECISION	HETEROGENEITY	INCOHERENCE	CONFIDENCE RATING
Krackow + TCR:PARS Midsubstance	0	Some concerns	Undetected	No concerns	No concerns	Major concerns	No concerns	Low
Krackow + TCR:Triple bundle	0	Some concerns	Undetected	No concerns	No concerns	Major concerns	No concerns	Moderate
Krackow + TM:MFSS	0	Some concerns	Undetected	No concerns	No concerns	Major concerns	No concerns	Low
Krackow + TM:PARS	0	Some concerns	Undetected	No concerns	No concerns	Major concerns	No concerns	Low
Krackow + TM:PARS Midsubstance	0	Some concerns	Undetected	No concerns	No concerns	Major concerns	No concerns	Low
Krackow + TM:Triple bundle	0	Some concerns	Undetected	No concerns	No concerns	Major concerns	No concerns	Low
MFSS:PARS	0	Some concerns	Undetected	No concerns	No concerns	Major concerns	No concerns	Low
MFSS:PARS Midsubstance	0	Some concerns	Undetected	No concerns	Major concerns	No concerns	No concerns	Low
MFSS:Triple bundle	0	Some concerns	Undetected	No concerns	Major concerns	No concerns	No concerns	Low
PARS:Triple bundle	0	Some concerns	Undetected	No concerns	No concerns	Major concerns	No concerns	Low
PARS Midsubstance:Triple bundle	0	Some concerns	Undetected	No concerns	Major concerns	No concerns	No concerns	Low

CINeMA report for each pairwise comparison in the network meta-analysis. Incoherence was assessed using the *netsplit* and *netheat* functions in *netmeta*. Kessler or Bunnell + Plantaris: augmentation of the repair with a plantaris tendon. Krackow + [biomaterial]: techniques in which the Krackow repair was augmented with a biomaterial; Cnx: Conexa; GrJ: GraftJacket; TCR: Trellis Collagen Ribbon; TM: TissueMend Soft Tissue Repair Matrix. DLKS: double loop knot sitch; MFSS: multifilament stainless steel. PARS: Percutaneous Achilles Repair System; PARS Midsubstance: augmentation of the PARS technique with suture anchors.

TABLE II-H | CINeMA report for elongation after cyclic loading network meta-analysis

COMPARISON	NUMBER OF STUDIES	WITHIN-STUDY BIAS	REPORTING BIAS	INDIRECTNESS	IMPRECISION	HETEROGENEITY	INCOHERENCE	CONFIDENCE RATING
Achillon:PARS	1	No concerns	Undetected	No concerns	Some concerns	No concerns	Some concerns	High
Achillon:PARS Midsubstance	1	No concerns	Undetected	No concerns	Major concerns	No concerns	Some concerns	Moderate
Achillon:Triple Kessler	1	No concerns	Undetected	No concerns	No concerns	No concerns	No concerns	High
Bunnell:Kessler	1	Some concerns	Undetected	No concerns	Major concerns	No concerns	No concerns	Low
Bunnell:Krackow	1	Some concerns	Undetected	No concerns	Some concerns	No concerns	No concerns	Moderate
DLKS:Kessler	1	No concerns	Undetected	No concerns	Some concerns	No concerns	No concerns	Moderate
Krackow:Krackow + GrJ	1	Some concerns	Undetected	No concerns	No concerns	No concerns	No concerns	Moderate
Krackow:Krackow + TCR	1	No concerns	Undetected	No concerns	No concerns	No concerns	No concerns	High
Krackow:Krackow + TM	1	No concerns	Undetected	No concerns	No concerns	No concerns	No concerns	High
Krackow:MFSS	1	Some concerns	Undetected	No concerns	Some concerns	No concerns	No concerns	Moderate
Krackow:PARS	1	Some concerns	Undetected	No concerns	No concerns	No concerns	No concerns	Moderate
Krackow:PARS Midsubstance	1	Some concerns	Undetected	No concerns	No concerns	No concerns	No concerns	Moderate

Continuation of table II-H

COMPARISON	NUMBER OF STUDIES	WITHIN-STUDY BIAS	REPORTING BIAS	INDIRECTNESS	IMPRECISION	HETEROGENEITY	INCOHERENCE	CONFIDENCE RATING
PARS:PARS Midsubstance	2	Some concerns	Undetected	No concerns	Some concerns	No concerns	No concerns	Moderate
PARS:Triple Kessler	1	No concerns	Undetected	No concerns	No concerns	No concerns	No concerns	High
PARS Midsubstance:Triple Kessler	1	No concerns	Undetected	No concerns	No concerns	No concerns	No concerns	High
Achillon:Bunnell	0	Some concerns	Undetected	No concerns	No concerns	No concerns	No concerns	Moderate
Achillon:DLKS	0	Some concerns	Undetected	No concerns	No concerns	No concerns	No concerns	Moderate
Achillon:Kessler	0	Some concerns	Undetected	No concerns	No concerns	No concerns	No concerns	Moderate
Achillon:Krackow	0	No concerns	Undetected	No concerns	No concerns	No concerns	No concerns	Moderate
Achillon:Krackow + GrJ	0	Some concerns	Undetected	No concerns	Some concerns	No concerns	No concerns	Moderate
Achillon:Krackow + TCR	0	No concerns	Undetected	No concerns	No concerns	No concerns	No concerns	Moderate
Achillon:Krackow + TM	0	No concerns	Undetected	No concerns	Some concerns	No concerns	No concerns	Moderate
Achillon:MFSS	0	Some concerns	Undetected	No concerns	Some concerns	No concerns	No concerns	Moderate
Bunnell:DLKS	0	Some concerns	Undetected	No concerns	Some concerns	No concerns	No concerns	Moderate
Bunnell:Krackow + GrJ	0	Some concerns	Undetected	No concerns	No concerns	No concerns	No concerns	Moderate
Bunnell:Krackow + TCR	0	Some concerns	Undetected	No concerns	Some concerns	No concerns	No concerns	Moderate
Bunnell:Krackow + TM	0	Some concerns	Undetected	No concerns	Some concerns	No concerns	No concerns	Moderate
Bunnell:MFSS	0	Some concerns	Undetected	No concerns	Some concerns	No concerns	No concerns	Moderate
Bunnell:PARS	0	Some concerns	Undetected	No concerns	No concerns	No concerns	No concerns	Moderate
Bunnell:PARS Midsubstance	0	Some concerns	Undetected	No concerns	No concerns	No concerns	No concerns	Moderate
Bunnell:Triple Kessler	0	Some concerns	Undetected	No concerns	No concerns	No concerns	No concerns	Moderate
DLKS:Krackow	0	Some concerns	Undetected	No concerns	Some concerns	No concerns	No concerns	Moderate

Continuation of table II-H

COMPARISON	NUMBER OF STUDIES	WITHIN-STUDY BIAS	REPORTING BIAS	INDIRECTNESS	IMPRECISION	HETEROGENEITY	INCOHERENCE	CONFIDENCE RATING
DLKS:Krackow + GrJ	0	Some concerns	Undetected	No concerns	No concerns	No concerns	No concerns	Moderate
DLKS:Krackow + TCR	0	Some concerns	Undetected	No concerns	Some concerns	No concerns	No concerns	Moderate
DLKS:Krackow + TM	0	Some concerns	Undetected	No concerns	Some concerns	No concerns	No concerns	Moderate
DLKS:MFSS	0	Some concerns	Undetected	No concerns	Major concerns	No concerns	No concerns	Low
DLKS:PARS	0	Some concerns	Undetected	No concerns	No concerns	No concerns	No concerns	Moderate
DLKS:PARS Midsubstance	0	Some concerns	Undetected	No concerns	No concerns	No concerns	No concerns	Moderate
DLKS:Triple Kessler	0	Some concerns	Undetected	No concerns	No concerns	No concerns	No concerns	Moderate
Kessler:Krackow	0	Some concerns	Undetected	No concerns	Some concerns	No concerns	No concerns	Moderate
Kessler:Krackow + GrJ	0	Some concerns	Undetected	No concerns	Major concerns	No concerns	No concerns	Low
Kessler:Krackow + TCR	0	Some concerns	Undetected	No concerns	Some concerns	No concerns	No concerns	Moderate
Kessler:Krackow + TM	0	Some concerns	Undetected	No concerns	Major concerns	No concerns	No concerns	Low
Kessler:MFSS	0	Some concerns	Undetected	No concerns	Major concerns	No concerns	No concerns	Low
Kessler:PARS	0	Some concerns	Undetected	No concerns	Some concerns	No concerns	No concerns	Moderate
Kessler:PARS Midsubstance	0	Some concerns	Undetected	No concerns	Some concerns	No concerns	No concerns	Moderate
Kessler:Triple Kessler	0	Some concerns	Undetected	No concerns	No concerns	No concerns	No concerns	Moderate
Krackow:Triple Kessler	0	No concerns	Undetected	No concerns	No concerns	No concerns	No concerns	High
Krackow + GrJ:Krackow + TCR	0	Some concerns	Undetected	No concerns	Major concerns	No concerns	No concerns	Low
Krackow + GrJ:Krackow + TM	0	Some concerns	Undetected	No concerns	Major concerns	No concerns	No concerns	Low

Continuation of table II-H

COMPARISON	NUMBER OF STUDIES	WITHIN-STUDY BIAS	REPORTING BIAS	INDIRECTNESS	IMPRECISION	HETEROGENEITY	INCOHERENCE	CONFIDENCE RATING
Krackow + GrJ:MFSS	0	Some concerns	Undetected	No concerns	Major concerns	No concerns	No concerns	Low
Krackow + GrJ:PARS	0	Some concerns	Undetected	No concerns	Some concerns	No concerns	No concerns	Moderate
Krackow + GrJ:PARS Midsubstance	0	Some concerns	Undetected	No concerns	Some concerns	No concerns	No concerns	Moderate
Krackow + GrJ:Triple Kessler	0	Some concerns	Undetected	No concerns	No concerns	No concerns	No concerns	Moderate
Krackow + TCR:Krackow + TM	0	No concerns	Undetected	No concerns	Major concerns	No concerns	No concerns	Low
Krackow + TCR:MFSS	0	Some concerns	Undetected	No concerns	Major concerns	No concerns	No concerns	Low
Krackow + TCR:PARS	0	Some concerns	Undetected	No concerns	Major concerns	No concerns	No concerns	Low
Krackow + TCR:PARS Midsubstance	0	Some concerns	Undetected	No concerns	Some concerns	No concerns	No concerns	Moderate
Krackow + TCR:Triple Kessler	0	No concerns	Undetected	No concerns	No concerns	No concerns	No concerns	High
Krackow + TM:MFSS	0	Some concerns	Undetected	No concerns	Major concerns	No concerns	No concerns	Low
Krackow + TM:PARS	0	Some concerns	Undetected	No concerns	Some concerns	No concerns	No concerns	Moderate
Krackow + TM:PARS Midsubstance	0	Some concerns	Undetected	No concerns	Some concerns	No concerns	No concerns	Moderate
Krackow + TM:Triple Kessler	0	No concerns	Undetected	No concerns	No concerns	No concerns	No concerns	High
MFSS:PARS	0	Some concerns	Undetected	No concerns	Some concerns	No concerns	No concerns	Moderate
MFSS:PARS Midsubstance	0	Some concerns	Undetected	No concerns	Some concerns	No concerns	No concerns	Moderate
MFSS:Triple Kessler	0	Some concerns	Undetected	No concerns	No concerns	No concerns	No concerns	Moderate

CINeMA report for each pairwise comparison in the network meta-analysis. Incoherence was assessed using the *netsplit* and *netheat* functions in *netmeta*. Krackow + [biomaterial]: techniques in which the Krackow repair was augmented with a biomaterial; Cnx: Conexa; GrJ: GraftJacket; TCR: Trellis Collagen Ribbon; TM: TissueMend Soft Tissue Repair Matrix. DLKS: double loop knot stitch; MFSS: multifilament stainless steel. PARS: Percutaneous Achilles Repair System; PARS Midsubstance: augmentation of the PARS technique with suture anchors

TABLE II-I | FAILURE MODES PER TECHNIQUE

TECHNIQUE	DISRUPTION OF SUTURE-TENDON INTERFACE	SUTURE/SCAFFOLD BREAKAGE	OTHER
Achillon	94.44%	5.56%	0.00%
Bunnell	15.63%	84.38%	0.00%
Bunnell + Plantaris	0.00%	0.00%	100.00%
Double Bunnell	0.00%	100.00%	0.00%
Double Kessler	0.00%	100.00%	0.00%
Double Krackow	0.00%	97.14%	2.86%
DLKS	37.5%	62.5%	0.00%
Kessler	86.67%	13.33%	0.00%
Kessler + Plantaris	0.00%	0.00%	100.00%
Krackow	0.00%	100.00%	0.00%
Krackow + Cnx	0.00%	0.00%	100.00%
Krackow + GrJ	0.00%	87.50%	12.50%
Krackow + TCR	0.00%	100.00%	0.00%
Krackow + TM	0.00%	20.00%	80.00%
MFSS	0.00%	100.00%	0.00%
PARS	28.21%	53.85%	17.95%
PARS Midsubstance	61.90%	0.00%	38.10%
Triple bundle	62.50%	37.50%	0.00%
Triple Kessler	100.00%	0.00%	0.00%
Total	28.49%	56.68%	14.83%

Failure modes per technique in percentage. Kessler or Bunnell + Plantaris: augmentation of the repair with a plantaris tendon. Krackow + [biomaterial]: techniques in which the Krackow repair was augmented with a biomaterial; Cnx: Conexa; GrJ: GraftJacket; TCR: Trellis Collagen Ribbon; TM: TissueMend Soft Tissue Repair Matrix. DLKS: double loop knot stitch; MFSS: multifilament stainless steel. PARS: Percutaneous Achilles Repair System; PARS Midsubstance: augmentation of the PARS technique with suture anchors.

TABLE II-J | FINDINGS OF INDIVIDUAL STUDIES

STUDY	FINDINGS
COMPARISONS BETWEEN SURGICAL TECHNIQUES	
Frosch et al. (2020)	Tendons were loaded for 1000 cycles with loads ranging from 5 to 20 N per cycle. Samples were stressed in the axial direction at a rate of 20 mm/s. All samples survived the cyclic loading procedure, with no statistically significant differences between the Kessler and double loop knot stitch (DLKS) groups ($p = 0.76$) and gap formation not exceeding 5 mm in both groups. Failure load was 110.27 ± 16.96 N for the Kessler and 107.15 ± 24.28 N DLKS groups (diferences were not statistically significant: $p = .85$).
Nguyen et al. (2020)	Load-to-failure was significantly higher ($p = 0.0078$) in the specimens repaired with the multifilament stainless steel (MFSS) cable-crimp technique (485.69 ± 47.93 N) in comparison with the Krackow stitch (378.71 ± 107.23 N). Gapping after cyclic loading was significantly ($p = 0.001$) lower with the MFSS technique (0.06 mm on average, versus 2 mm with the Krackow stitch).
Cottom et al. (2017)	Load-to-failure was higher in specimens repaired with the PARS Midsubstance technique (385.91 ± 117.02 N) in comparison with the traditional Krackow stitch (283.86 ± 114.64 N) and PARS (206.40 ± 20.52 N), but the difference was not statistically significant ($p = 0.098$). Displacement after 1000 cycles was lowest in the PARS Midsubstance group and this was the only outcome in which differences had statistical significance ($p = 0.04$).
Van Dyke et al. (2017)	Tendons were loaded for 1000 cycles with loads between 10 and 100 N. Surviving specimens were loaded to failure. Two tendons in the Bunnell group failed during cyclic loading, compared with zero on the "Giftbox" Krackow group ($p = 0.48$). Six tendons in the Bunnell group exhibited measurable gapping, compared with one in "Giftbox" Krackow group ($p = 0.059$). Differences between the "Giftbox" in mean gapping of repair, gapping and stiffness after 1000 cycles were statistically significant (respectively: 0.13 ± 0.5 mm versus 2.29 ± 2.6 mm, $p = 0.02$; 5.8 ± 0.8 mm versus 4.5 ± 1.0 mm, $p = 0.012$; 47.5 ± 5.5 N/mm versus 38.7 ± 9.2 mm; $p = 0.019$).
Clanton et al. (2015)	Cyclic testing consisted of four blocks of 250 cycles at 20-100 N, 20-200 N, 20-300 N and 20-400 N. No failures were observed in any of the groups in the first 250 cycles, but no specimens survived all 1000 cycles of loading. The augmented triple Kessler repairs suffered less elongation after 250 cycles (5.2 ± 1.1 mm) than the Achillon, PARS or PARS Midsubstance repairs (9.9 ± 2.2 mm, 12.2 ± 4.4 mm, and 10.0 ± 3.9 mm, respectively) ($p < 0.05$). The largest proportion of the gapping occurred in the first 10 cycles: 71.2% (3.7 ± 0.8 mm) for the triple Kessler, 81.8% (8.1 ± 2.3 mm) for the Achillon, 77.9% (9.5 ± 4.3 mm) for the PARS, and 69.0% (6.9 ± 2.4 mm) for PARS Midsubstance repairs, during the first 250 cycles. Differences in number of cycles to failure were not significantly different between groups (triple Kessler 439 ± 122 cycles, Achillon 362 ± 113, PARS 424 ± 203, and PARS Midsubstance 441 ± 201).

Continuation of table II-J

STUDY	FINDINGS
Demetracopoulos et al. (2014)	Mean load-to-failure was 385.0 (185.6-502.2) N in specimens repaired with the PARS technique and was 299.6 (186.6-316.6) N in specimens repaired with the Achillon technique (p = 0.001). Comparing the Achillon and PARS techniques in regard to number of cycles to 2.0- (16.0 (3-143) versus 59.0 (6-1008)), 5.0- (1002.0 (170-1013) versus 1004.0 (91-1223)) and 9.5 mm gaps (1065.5 (1001-1204) versus 1288.0 (1003-6340)) favored the PARS repair, but the difference was statistically significant only for the 2.0- and 9.5 mm gaps (p = 0.012 and p = 0.005, respectively).
Heitman et al. (2011)	Average load-to-failure for repairs with the Krackow stitch was 128.3 ± 30.3 N compared with the 142.4 ± 62.3 N for repairs with the Achillon technique (p = 0.63). Differences between groups were only statistically significant if three outliers from the Achillon group were removed (178.0 ± 35.4 N; p < 0.05). Work-to-failure (calculated from the area under the load-displacement curve) was not significantly different between groups. Repairs with the Krackow stitch had an higher initial stiffness than those repaired with the Achillon technique (p < 0.05).
McCoy et al. (2010)	The mean load-to-failure was 196 ± 45 N for the double Bunnell, 200 ± 20 N for the double Krackow, and 167 ± 51 N for the double Kessler. These differences were not statistically significant (p = 0.24).
Herbort et al. (2008)	Mean elongation after 10, 100, 500, 750 and 1000 cycles at 5-20 N was 1.05 ± 0.2, 2.86 ± 0.7, 4.86 ± 1.4, 5.48 ± 1.6, and 5.96 ± 1.9 mm, respectively, for the Bunnell stitch. For repairs using the Kessler stitch these values were 1.25 ± 0.3, 3.29 ± 1.2, 4.95 ± 1.7, 5.33 ± 1.8, and 5.58 ± 1.8 mm, respectively. Differences were not statistically significant. Load-to-failure was 255.033 ± 22.45 N for the Bunnell stitch and 192.768 ± 51.26 N (p < 0.05). Yield load and stiffness were similar in both groups.
Huffard et al. (2008)	A statistically significant difference in the mean load-to-failure of both repairs was found (p = 0.03), favoring the Achillon technique (342 ± 92.8 N) against the double Krackow technique (276 ± 87.0 N).
Jaakkola et al. (2000)	Mean load-to-failure was 453 ± 53.9 N for the specimens repaired with the triple bundle technique and 161 ± 31.1 N for the double Krakow group (p < 0.001).
COMPARISONS WITH AUGMENTATION PROCEDURES	
Berlet et al. (2014)	Evaluated the load-to-failure and gap formation after 20 cycles with and without a collagen ribbon augmentation (Trellis Collagen Ribbon, Wright Medical Group) using a box weave. The mean load-to-failure for the augmented group was 392.4 ± 74.9 N compared to 98.8 ± 17.6 N in the non-augmented group (p < 0.006). Elongation after 20 cycles was 0.7 ± 0.7 mm in the augmented group compared with 4.6 ± 3.9 mm in the non-augmented group (p = 0.006).
Wisbeck et al. (2012)	Load-at-5 mm gap was 333.2 ± 105.4 in the augmented group and 156.7 ± 42.9 in non-augmented group (p = 0.01). Load-to-failure was 862.7 ± 174 N in the augmented group versus 479.5 ± 65.5 N in the non-augmented group (p < 0.01). Initial stiffness was also higher in the augmented repairs (39.0 ± 8.8 N/mm versus 24.4 ± 4.6 N/mm in the augmented versus non-augmented groups, respectively; p = 0.01), but differences were not statistically significant after 200 cycles.

Continuation of table II-J

STUDY	FINDINGS
Magnussen et al. (2011)	Tested elongation after 1000 cycles and load-to-failure of the augmentation with a bovine extracellular matrix xenograft (TissueMend Soft Tissue Repair Matrix; TEI Biosciences, Inc/Stryker Orthopaedics, Mahwah, New Jersey).(30) The graft was secured to the repair with eight mattress sutures. Elongation after cyclic loading was less pronounced in the augmented group (4.0 ± 0.7 mm) than in the non-augmented group (6.5 ± 1.6 mm) ($p < 0.01$). Load-to-failure was also higher in the augmented group (821 ± 123 N) compared with the non-augmented group (392 ± 46 N) ($p < 0.005$). Augmented repairs were also stiffer than non-augmented repairs (38.2 ± 11.7 N/mm versus 18.8 ± 4.3 N/mm, respectively) ($p < 0.01$). Significantly less elongation occurred after 10 cycles in the augmented group.
Barber et al. (2008)	Tested augmentation with an acellular allograft dermal matrix (GraftJacket, Wright Medical Group).(52) Load-to-failure was higher in tendons repaired using augmentation than in non-augmented group (455.1 ± 76.5 N versus 216.8 ± 31.1 N, respectively; $p < 0.001$). Stiffness was also higher in the augmented group ($p = 0.002$). Augmented repairs also experienced less creep during cyclic loading ($p = 0.053$).
Gebauer et al. (2007)	Compared the load-to-failure values of different suture combinations in Kessler and Bunnell repairs.(36) They used No. 1 PDS-Thread, No.5 PDS-Cord and reinforcement with plantaris tendon. Repairs in the Bunnell group were stronger than those in the Kessler group. Repairs performed using PDS-Cord were stronger than those performed using PDS-Thread (291 ± 55.2 N versus 139 ± 29.8, respectively, in the Bunnell group; and 180 ± 41.1 N versus 137 ± 37.3 N, respectively, in the Kessler group). The addition of a plantaris tendon augmentation to a PDS-Thread using a Bunnell stitch provided the highest load-to-failure in this study (326 ± 124.9 N).

Description of findings in each individual study, with references. All values represented as means and standard deviations, except where stated otherwise.

TABLE II-K | FINDINGS OF STUDIES NOT INCLUDED IN THE QUANTITATIVE SYNTHESIS

STUDY	FINDINGS
Mortensen et al. (1991)	Mean load-to-failure was 45 ± standard error of the mean (SEM) 3.4 N for the Mason group, 78 ± SEM 6.6 N for the Bunnell group, and 175 ± SEM 12.0 N. At 40 N of static tension, the Mason group suffered a mean gapping of 21.9 mm, the Bunnell group 11.8 mm, and the CSSS group 2.7 mm.
Watson et al. (1995)	Mean load-to-failure was higher for the double Krackow group (147.18 ± 21.20) compared with the Kessler (85.24 ± 4.97 N) and Bunnell (93.18 ± 11.82 N) groups. This difference was statistically significant ($p < 0.0015$).
Zandbergen et al. (2005)	Assessed the load-to-failure of different configurations of a Bunnell repair using either No. 1 PDS-II, No. 1 Panacryl or augmentation with Mitek suture anchors. Three techniques were used: open Bunnell stitch with PDS-II; percutaneous Bunnell stitch in the proximal stump with the sutures going through a calcaneal tunnel, with PDS-II and Panacryl; and percutaneous Bunnell stitch in the proximal stump with the sutures fixed to the calcaneus using suture anchors. The load-to-failure mean values ranged from 166 ± 60 to 211 ± 30 across the five groups, but no significant differences could be found between the different techniques ($p = 0.5$).
Lee et al. (2017)	Specimens were loaded for 1000 cycles from 20-100 N; surviving specimens were loaded for another 1000 cycles from 20-190 N, surviving specimens were then loaded for another 1000 cycles from 20-369 N. Number of cycles to initial gapping was highest for the augmented Krackow stitch (2208 (2005-3000)), comparing with the Krackow (502 (90-1070)) and Achillon repairs (5.0 (1-9)) ($p = 0.24$). Number of cycles to 5 mm gap was 2213 (2006-3000) for the augmented Krackow, 741 (200-1206) for the non-augmented Krackow, and 22 (9-35) for the Achillon technique ($p = 0.024$). Number of cycles to failure was 2213 (2007-3000) for the augmented Krackow, 1268 (1010-1690) for the non-augmented Krackow, and 102 (13-340) for the Achillon technique ($p = 0.024$).
Giza et al. (2011)	Tested augmentation with a synthetic degradable scaffold (Artelon Tissue Reinforcement implant (Artimplant AB, Västra Frölunda, Sweden). Load-to-failure was significantly higher in the group repaired with scaffold augmentation (370.4 ± 25.2 N) compared with non-augmented group (248.1 ± 19.6 N) ($p = 0.0015$). Stiffness and length at failure were also higher in the augmented group, but differences in stiffness were not statistically significant ($p = 0.137$ and 0.033, respectively). Augmented repairs experienced less creep during cyclic loading ($p = 0.026$).
Manent et al. (2017)	Tendons were loaded for 1000 cycles with loads between 10 and 100 N. Double Kessler and Ma & Griffith had a higher rupture percentage (2 out of 7, 28.6%; comparing with 1 out of 7, 14.28% in the Krackow and Double Bunnell). Ma & Griffith suffered the highest tendon elongation (7.72 ± 3.59 mm), followed by the Krackow group (7.11 ± 5.84 mm), double Kessler (5.23 ± 1.04 mm) and double Bunnell (4.53 ± 3.07 mm). These differences were not statistically significant ($p = 0.772$).

Continuation of table II-K

STUDY	FINDINGS
Yang et al. (2018)	A Bunnell stitch, Bosworth technique and a Bunnell repair augmented with suture anchors were compared. The maximal load of specimens repaired with the augmented Bunnell had a higher maximal load (176.09 ± 23.54 N) than those in the Bunnell and Bosworth techniques (111.36 ± 4.94 and 111.74 ± 9.94 N, respectively) ($p < 0.05$).
Wagner et al. (2019)	Compared strength of fixation during cyclic loading in proximal and distal stumps using triple-locking, Bunnell-type and double Bunnell-type techniques. The distal fixation site was significantly weaker ($p = 0.001$) and more prone to elongation than the distal site (13.7 mm, $p = 0.02$).

Description of findings in each study, with references. All values represented as means and standard deviations, except where stated otherwise.

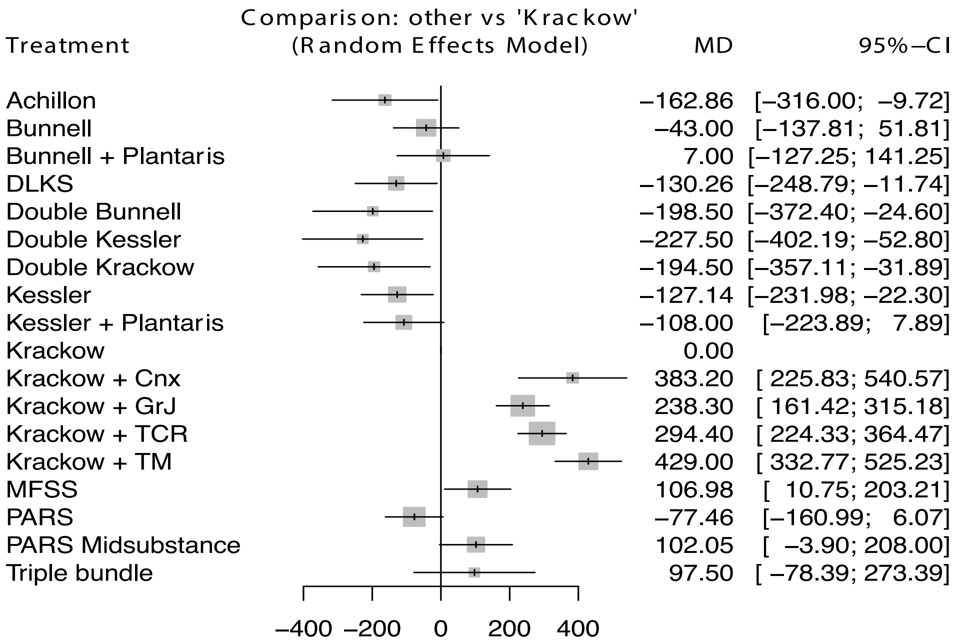


FIGURE II-A | FOREST PLOT OF THE LOAD-TO-FAILURE NETWORK META-ANALYSIS, USING THE KRACKOW STITCH AS REFERENCE COMPARATOR. Kessler or Bunnell + Plantaris: augmentation of the repair with a plantaris tendon. Krackow + [biomaterial]: techniques in which the Krackow repair was augmented with a biomaterial; Cnx: Conexa; GrJ: GraftJacket; TCR: Trellis Collagen Ribbon; TM: TissueMend Soft Tissue Repair Matrix. DLKS: double loop knot stitch; MFSS: multifilament stainless steel; PARS: Percutaneous Achilles Repair System; PARS Midsubstance: augmentation of the PARS technique with suture anchors.

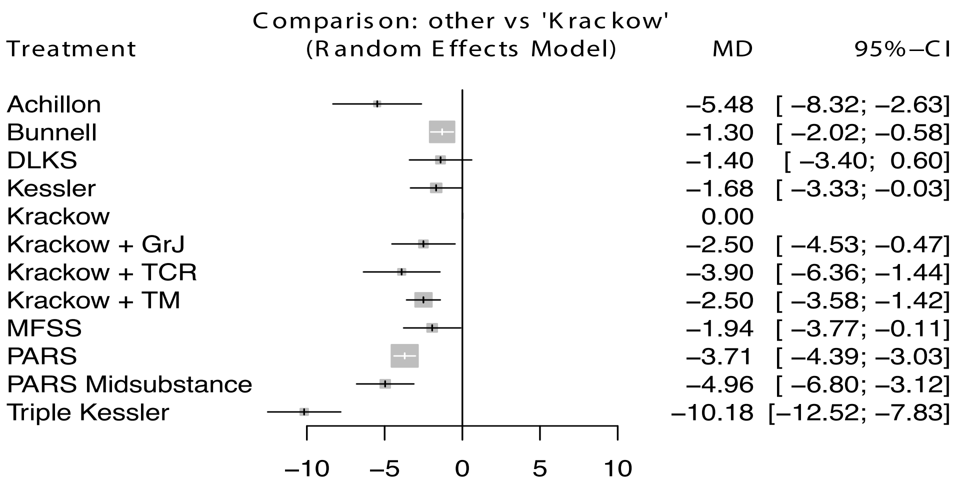


FIGURE II-B | FOREST PLOT OF THE ELONGATION WITH CYCLIC LOADING NETWORK META-ANALYSIS, USING THE KRACKOW STITCH AS REFERENCE COMPARATOR. Kessler or Bunnell + Plantaris: augmentation of the repair with a plantaris tendon. Krackow + [biomaterial]: techniques in which the Krackow repair was augmented with a biomaterial; GrJ: GraftJacket; TCR: Trellis Collagen Ribbon; TM: TissueMend Soft Tissue Repair Matrix. DLKS: MFSS: multifilament stainless steel; PARS: Percutaneous Achilles Repair System; PARS Midsubstance: augmentation of the PARS technique with suture anchors.

APPENDIX III
Supplementary material for Chapter 10

LITERATURE REVIEW

When multiple studies provided relevant data for the same parameter, weighted averages were computed based on the patient population in each study.

Systematic review of complication rates

Patients of all ages, occupations, and activity levels were considered. Studies included in the current literature review were required to report the use of early functional rehabilitation protocols, defined as starting weight-bearing and exercise-based interventions within two weeks after acute ATR rupture or repair. A minimum follow-up of at least one year was required.

The following reasons were considered for exclusion of studies from the systematic review: studies related to open or chronic injuries, studies comparing the results of mechanical or biological augmentation procedures, and studies performed on animal models or cadavers. Systematic reviews, clinical trial registrations, and conference proceedings were considered as sources of primary studies only. Case reports, narrative review papers, and expert opinions were excluded. Due to limitations of the research team regarding languages spoken and access to translators, only articles in English, French, Dutch, and Spanish were considered eligible for inclusion.

The databases for PubMed, CENTRAL, and Web of Science were searched. No time or language restrictions were applied. Relevant references extracted from the articles screened were included for analysis as well. Searches were conducted on January 24th of 2021. The following search string was used: (((Achilles OR calcaneal OR calcaneus OR calcanean) AND (tendon OR tendo)) OR (tendoachilles OR tendocalcaneus)) AND (repair OR suture* OR surgery OR treatment OR management OR conservative OR non-operative) AND (compared OR comparative OR versus OR (randomized AND controlled AND trial) OR RCT) NOT (tendinopath* OR chronic). Two reviewers independently screened and selected studies for complete text analysis from title and abstract using the Rayyan QCRI systematic review management app [31]. Disagreement was settled by discussion.

The full text of all relevant references was screened for eligibility and other references that may have been of interest.

Customized forms, Microsoft Excel and Rayyan QCRI were used for data management. Both reviewers performed data collection, and data were extracted in duplicate. The following data items were collected: authors, year of publication, treatment(s), demographic data, and complications rates (re-rupture, minor and severe wound healing complications, superficial and deep infection, and nerve injury).

The search yielded 4133 entries. After removing duplicate entries, 2874 records were screened, and 210 were selected for full-text evaluation. After the application of eligibility criteria, seven papers were selected for inclusion [12, 16, 20, 22, 26, 29, 36].

TABLE III-S1 | DEMOGRAPHIC DATA FROM INCLUDED STUDIES

STUDY	INTERVENTIONS (N)			PARTICIPANTS (N)			MALES (%)	AGE (YEARS)			FOLLOW-UP (YEARS)
	A	B	C	A	B	C		A	B	C	
Fischer et al. (2020)[12]	OS	MIS	EFR	30	30	30	90	39.6 ± 7.3	39.3 ± 7.9	45.2 ± 9.5	2
Manent et al. (2019)[20]	EFR	MIS	OS	11	11	12	91.2	42 (26-51)	41 (18-50)	40.5 (28-51)	1
Lantto et al. (2016)[16]	OS	EFR		32	28		91.7	40 (27-57)	39 (28-60)		1.5
Olsson et al. (2013)[29]	OS	EFR		49	51		86	39.8 ± 8.9	39.5 ± 9.7		1
Willits et al. (2010)[36]	OS	EFR		72	72		81.9	39.7 ± 11.0	41.1 ± 8.0		2
Möller et al. (2002)[22]	OS	EFR		59	53		88.4	39.1 ± 8.2			2
Nistor (1981)[26]	OS	EFR		45	60		91.4	41 (21-77)			1*
Batista et al. (2020)[3]#	FHL			56			100	36.39 ± 8.1			1.5*
Nilsson-Helander et al. (2008)[25]	ORS			28			78.6	46 ± 10.4			1*

#: Prospective case series. *: Minimum follow-up. CT: conservative treatment. FHL: endoscopic flexor hallucis longus transfer. MIS: minimally invasive surgery. OS: open surgery. ORS: open revision surgery. Values represented as means and standard deviations or percentages of total values, except otherwise specified.

TABLE III-S2 | OUTCOME DATA FROM INCLUDED STUDIES

STUDY	INTERVENTIONS			RE-RUPTURE			MINOR WHP			MAJOR WHP			SURAL N.INJURY			DVT		
	A	B	C	A	B	C	A	B	C	A	B	C	A	B	C	A	B	C
Fischer et al. (2020)[12]	OS	MIS	EFR	1	1	2	5	3	1	0	0	0	0	0	3	0	1	0
Manent et al. (2019)[20]	EFR	MIS	OS	0	0	0	0	0	0	0	0	0	0	2*	2†	0	0	0
Lantto et al. (2016)[16]	OS	EFR		1	4		0	0		1	0		0	0		0	0	
Olsson et al. (2013)[29]	OS	EFR		0	5		17	2		0	0		1	0		1	2	
Willits et al. (2010)[36]	OS	EFR		2	4		6	0		1	0		0	1*		2	1	
Möller et al. (2002)[22]	OS	EFR		1	11		0	0		0	0		0	0		0	0	
Nistor (1981)[26]	OS	EFR		2	5		2	0		0	0		9	0		0	0	
Batista et al. (2020)[3]	FHL			1			2			0			2†			1		
Nilsson-Helander et al. (2008)[25]	ORS			0			3			1			2			2		

†: Focal numbness or chronic pain, not sural nerve injury specifically. *: Disappeared after one year. CT: conservative treatment. FHL: endoscopic flexor hallucis longus transfer. MIS: minimally invasive surgery. OS: open surgery. ORS: open revision surgery. Values represented as number of cases in each study group.

COSTS

TABLE III-S3 | MEDICAL BILLING CODES INCLUDED IN THE ECONOMIC MODEL

CATEGORY	COST ITEM	CODE	DESCRIPTION
Imaging studies	MRI	73721	Magnetic resonance (e.g., proton) imaging, any joint of lower extremity; without contrast material
	Doppler US	93970-1	Duplex ultrasound study: Extremity veins incl. responses to compression and other maneuvers
Office visits	New patient visit	99202-5	Office or other outpatient visit for the evaluation and management of a new patient (...)
	Established patient visit	99211-5	Office or other outpatient visit for the evaluation and management of an established patient (...)
Rehabilitation	Physical therapy	97010	Application of a modality to 1 or more areas; hot or cold packs
		97014	Application of a modality to 1 or more areas; electrical stimulation (unattended)
		97032	Application of a modality to 1 or more areas; electrical stimulation (manual) (…)
		97035	Application of a modality to 1 or more areas; ultrasound (…)
		97110	Therapeutic procedure, (…); therapeutic exercises to develop strength and endurance, range of motion and flexibility
		97112	Therapeutic procedure, (…); neuromuscular reeducation of movement, balance, coordination, kinesthetic sense (…)
		97140	Manual therapy techniques (e.g., mobilization/ manipulation, manual lymphatic drainage, manual traction) (…)
		97162	Physical therapy evaluation: moderate complexity (...)
		97164	Re-evaluation of physical therapy established plan of care (…)
		97530	Therapeutic activities, direct (one-on-one) patient contact (use of dynamic activities to improve functional performance) (…)

Continuation of table III-S3

CATEGORY	COST ITEM	CODE	DESCRIPTION
Surgical Procedures	Surgery A	27650	Repair, primary, open or percutaneous, ruptured Achilles tendon
		27652	Repair, primary, open or percutaneous, ruptured Achilles tendon; with graft (…)
	Surgery B*	27690-1	Transfer or transplant of single tendon (with muscle redirection or rerouting); (...)
		28118	Ostectomy, calcaneus; for spur, with or without plantar fascial release
	Revision surgery	27654	Repair, secondary, Achilles tendon, with or without graft
	Anesthesia A	01472	Anesthesia to repair calf muscle tendon
	Anesthesia B	01470	Anesthesia for procedures on nerves, muscles, tendons, and fascia of lower leg, ankle, and foot
	Anesthesia C	01250	Anesthesia for procedure on nerves, muscles, tendons, fascia, and bursae of upper leg
	Wound debridement	10140	Incision and drainage of hematoma, seroma or fluid collection
		10160	Incision and drainage of abscess (carbuncle, suppurative hidradenitis, cutaneous or subcutaneous abscess, cyst, furuncle, or paronychia); simple or single and complex or multiple.
		10180	Incision and drainage, complex, postoperative wound infection
		11042-4	Debridement, muscle and/or fascia (…)
		27603	Incision and drainage, leg or ankle; deep abscess or hematoma
		15003	Surgical preparation or creation of recipient site by excision of open wounds, burn eschar, or scar (including subcutaneous tissues), or incisional release of scar contracture
		97597	Debridement (e.g., high pressure waterjet with/without suction, sharp selective debridement with scissors, scalpel and forceps), open (…)
	Primary closure	13160	Secondary closure of surgical wound or dehiscence, extensive or complicated
	Skin grafting or flap surgery	15271	Application of skin substitute graft to trunk, arms, legs, total wound surface area up to 100 sq cm; (…)
		15738	Muscle flap wound repair of lower extremity
Other procedures	Wound care	10060-1	Incision and drainage of abscess (carbuncle, suppurative hidradenitis, cutaneous or subcutaneous abscess, cyst, furuncle, or paronychia); simple or single and complex or multiple
		10160	Aspiration of abscess, blood accumulation, blister, or cyst
		97602	Removal of devitalized tissue from wound(s), non-selective debridement, without anesthesia (...)

Continuation of table III-S3

CATEGORY	COST ITEM	CODE	DESCRIPTION
Medical equipment and implants	Splint	29345	Application of long leg cast (thigh to toes)
		29405	Application of short leg cast (below knee to toes)
		29515	Application of short leg splint (calf to foot)
	Brace	L4360	Walking boot, pneumatic and/or vacuum, (...) customized to fit a specific patient by an individual with expertise
		L4361	Walking boot, pneumatic and/or vacuum, with or without joints, with or without interface material, prefabricated, off-the-shelf
		L4386	Walking boot, non-pneumatic, with or without joints, with or without interface material, prefabricated (...) customized to fit a specific patient by an individual with expertise
		L4387	Walking boot, non-pneumatic, with or without joints, with or without interface material, prefabricated, off-the-shelf
	Interference screw	C1713	Anchor/screw for opposing bone-to-bone or soft tissue-to-bone (implantable)

Current Procedural Terminology (CPT) codes used to retrieve average prices from public access database. MRI: magnetic resonance imaging. US: ultrasound. *: Used only for price estimation.

TABLE III-S4 | QUANTITIES PER COST ITEM

NODE	COST ITEM	BASELINE	RANGE	SOURCE
TREATMENTS				
Common to all treatments	New patient office visits	1	N/A	EO
	MRI	1	N/A	EO
	Splint	1	N/A	EO
	Functional brace	1	N/A	EO
EFR	Established patient office visits	10.9	2 to 14	[10, 13, 34, 35]
	Duration of sick leave in days	49.6	1 to 180	[1, 2, 7, 15, 23, 35], EO
	Physical therapy sessions	12.4	6 to 64	[34, 35]
Surgical treatments	Established patient office visits	4.6	2 to 14	[6, 10, 13, 19, 34, 35]
	Duration of sick leave in days	53.5	1 to 180	[7, 9, 14, 17, 23, 35]
	Physical therapy sessions	8.8	6 to 64	[18, 34, 35], EO
Open surgery	Surgery A	1	N/A	EO
	Anesthesia A	1	N/A	EO
Minimally invasive surgery	Percutaneous repair jig	1	N/A	EO
	+ Open surgery			
FHL transfer	Surgery B	1	N/A	EO
	Anesthesia B	1	N/A	EO
	Interference screw	1	N/A	EO
HEALTH EVENTS				
Re-rupture	Additional established patient office visits	*Same as primary ruptures*		EO
	MRI	1	N/A	EO
	Revision surgery	1	N/A	EO
	Anesthesia A	1	N/A	EO
	Additional physical therapy sessions	*Same as primary ruptures*		EO
	Additional days of sick leave	90	7 to 180	[25], EO

Continuation of table III-S4

NODE	COST ITEM	BASELINE	RANGE	SOURCE
Minor WHP	Additional established patient office visits	2.1	0-4	[4], EO
	Wound care in office	1	1-10	[4]
	Oral ciprofloxacin 750 mg	14	14 to 28	EO
	Additional days of sick leave	14	0 to 30	EO
Major WHP	Additional established patient office visits	3	3 to 10	EO
	Wound debridement in OR	1	1 to 3	[5]
	Primary closure, skin grafting, or flap surgery	1	N/A	[5]
	Anesthesia C	2	2 to 4	[5]
	Vancomycin 1 g IV	34	21 to 42	[5]
	Additional days of sick leave	90	30 to 180	EO
Sural nerve injury	Additional established patient office visits	1	1 to 3	EO
	Gabapentin 300 mg	218	218 to 365	[33]
Deep venous thrombosis	Additional established patient office visits	3.5	3 to 20	EO
	Doppler US	2	N/A	[24]
	Rivaroxaban 15 mg	42	N/A	[30]
	Rivaroxaban 20 mg	48	48 to 159	[30]

EFR: early functional rehabilitation. EO: expert opinion. IV: intravenous. MRI: magnetic resonance imaging. N/A: not applicable. US: ultrasound. WHP: wound healing problems.

TABLE III-S5 | UNITARY PRICE PER COST ITEM

COST ITEM	BASELINE	RANGE	SOURCE
DIRECT COSTS			
OFFICE VISITS			
New patient office visits	$536.5	$187.2 to $925.3	[11]
Established patient office visits	$312.4	$131.1 to $607.1	[11]
IMAGING			
MRI	$1806.9	$1355.2 to $2258.63	[11]
Doppler US	$1211.25	$958.55 to $1463.95	[11]
SUPPLIES			
Splint	$1108.65	$883.5 to $1468.7	[11]
Percutaneous repair jig	$800	$0 to $1000	EO
Interference screw	$375.25	$281.44 to $469.06	[11]
Functional brace	$179.31	$95 to $270.75	[11]
PHYSICAL THERAPY			
Physical therapy sessions	$126.45	$48.45 to $338.2	[11]
PROCEDURES			
Surgery A	$9340.88	$6916.24to $11527.06	[11]
Surgery B*	$9340.88	$6916.24 to $11527.06	EO
Revision surgery	$4678.75	$3509.06 to $5848.44	[11]
Wound care in office	$474.34	$253.65 to $767.6	[11]
Wound debridement in OR	$1931.23	$297.35 to $4366.2	[11]
Primary closure, skin grafting, or flap surgery	$3822.48	$1787.9 to $5162.3	[11]
Anesthesia A	$935.75	$701.81 to $1169.69	[11]
Anesthesia B	$646	$484.5 to $807.5	[11]
Anesthesia C	$851.2	$638.4 to 1064	[11]
DRUGS			
Oral ciprofloxacin 750 mg	$1.27	$1.05 to $1.48	[21]
Vancomycin 1 g IV	$2.70	$0.08 to $10.63	[21]
Gabapentin 300 mg	$0.74	$0.56 to $0.93	[21]
Rivaroxaban 15 mg	$14.85	$11.14 to $18.56	[21]
Rivaroxaban 20 mg	$14.85	$11.14 to $18.56	[21]
INDIRECT COSTS			
Sick leave (per day)	$27.07	$13.3 to $60.81	[27]

Price per unit in 2019 United States of America Dollars. EFR: early functional rehabilitation. EO: expert opinion. IV: intravenous. MRI: magnetic resonance imaging. N/A: not applicable. US: ultrasound. WHP: wound healing problems. *: arbitrarily defined as costing the same as primary Achilles tendon repair.

TABLE III-S6 | MODEL PARAMETERS FOR THE REFERENCE CASE AND ONE-WAY SENSITIVITY ANALYSIS

ITEM	REFERENCE CASE	ONE-WAY SENSITIVITY ANALYSIS	SOURCE
DIRECT COSTS			
OFFICE VISITS			
New patient visits	$536.5	$187.2 to $925.3	[11]
Conservative treatment, established patient office visits	$3,405.16	$374.40 to $12,954.20	[10, 11, 13, 34, 35]
Surgical treatments, established patient office visits	$1,437.04	$374.40 to $12,954.20	[6, 10, 11, 13, 19, 34, 35]
Re-rupture, additional established patient office visits	$1,437.04	$374.40 to $12,954.20	EO
Minor WHP, additional established patient office visits	$656.04	$0 to $2,428.4	[4], EO
Major WHP, additional established patient office visits	$937.20	$393.3 to $6,071	EO
Sural nerve injury, additional established patient office visits	$312.40	$131.1 to $1,821.3	EO
DVT, additional established patient office visits	$1,093.40	$393.3 to $12,142	EO
MEDICAL IMAGING			
Magnetic resonance imaging	$1,806.9	$1,355.2 to $2,258.63	[11]
Doppler Ultrasound	$2,422.50	$1,917.1 to $2,927.9	[11, 24]
SUPPLIES			
Splint	$1108.65	$883.5 to $1468.7	[11]
Functional brace	$179.31	$95 to $270.75	[11]
Percutaneous repair jig	$800	$0 to $1,000	EO
Interference screw	$375.25	$281.44 to $469.06	[11]
PHYSICAL THERAPY			
Conservative treatment, cost of rehabilitation	$1,567.98	$290.7 to $17,328	[11, 34, 35], EO
Surgical treatments, cost of rehabilitation	$1,112.76	$290.7 to $17,328	[11, 18, 34, 35], EO
PROCEDURES			
Primary Achilles tendon repair	$9,340.88	$6,916.24to $11,527.06	[11]
Endoscopic flexor hallucis longus transfer	$9,340.88	$6,916.24 to $11,527.06	EO
Revision surgery[#]	$4,678.75	$3,509.06 to $5,848.44	[11]
Wound care in office	$474.34	$253.65 to $7,676	[4, 11], EO

Continuation of table III-S6

ITEM	REFERENCE CASE	ONE-WAY SENSITIVITY ANALYSIS	SOURCE
Wound debridement in OR	$1,931.23	$297.35 to $13,098.6	[5, 11]
Primary closure, skin grafting, or flap surgery	$3,822.48	$1,787.9 to $5,162.3	[5, 11]
Anesthesia A	$935.75	$701.81 to $1,169.69	[11]
Anesthesia B	$646	$484.5 to $807.5	[11], EO
Anesthesia C	$1,702.40	$1,276.8 to $4,256	[5, 11]
DRUGS			
Oral ciprofloxacin 750 mg	$17.78	$14.7 to $41.44	[21], EO
Vancomycin 1 g IV	$91.80	$1.68 to $446.46	[5, 21]
Gabapentin 300 mg	$161.32	$122.08 to $339.45	[21, 33]
Rivaroxaban 15 mg	$623.70	$467.88 to $779.52	[21, 30]
Rivaroxaban 20 mg	$712.80	$534.72 to $2,951.04	[21, 30]
INDIRECT COSTS			
Conservative treatment, sick leave	$1,342.67	$13.3 to $10,945.80	[1, 2, 7, 15, 23, 27, 35], EO
Surgical procedures, sick leave	$1,448.25	$13.3 to $10,945.80	[7, 9, 14, 17, 23, 27, 35], EO
Re-rupture, additional days of sick leave	$2,436.3	$93.1 to $10,945.8	[25], EO
Minor WHP, additional days of sick leave	$387.8	$0 to $1,824.3	EO
Major WHP, additional days of sick leave	$2493	$399 to $10,945.8	EO
OTHER			
Re-rupture, days elapsed since primary treatment	78	49 to 115	[32], EO
UTILITIES*			
CONSERVATIVE TREATMENT			
QALYs first 3 months after injury	0.74	0.6 to 0.9	[8, 28, 35]
QALYs 3 to 6 months after injury	0.85	0.62 to 1	[8, 29, 35]
QALYs 6 to 24 months after injury	0.89	0.7 to 1	[8, 29, 35]
SURGICAL TREATMENTS			
QALYs first 3 months after injury	0.75	0.6 to 0.8	[8, 28, 35]
QALYs 3 to 6 months after injury	0.87	0.7 to 1	[8, 29, 35]
QALYs 6 to 24 months after injury	0.93	0.9 to 1	[8, 29, 35]

#: Cost of revision surgery for re-rupture patients initially treated with endoscopic flexor hallucis longus transfers since these are treated conservatively. *: Utilities are discounted by 10% during the first year in minor complications and by 20% throughout the study period in major complications. DVT: deep venous thrombosis. EO: Expert opinion. OR: operations room. QALY: Quality-adjusted life-years. WHP: wound healing problems.

TABLE III-S7 | DISTRIBUTION OF DIRECT COSTS IN THE REFERENCE CASE ANALYSIS

	PRIMARY TREATMENT	COMPLICATIONS					TOTAL
		RE-RUPTURE	MINOR WHP	MAJOR WHP	SURAL NERVE INJURIES	DVT	
Conservative	$8.6 x 10⁸ (88.38%)	$9.82 x 10⁷ (10.09%)	$2.4 x 10⁶ (0.25%)	$3.12 x 10⁶ (0.32%)	$9.60 x 10⁵ (0.1%)	$8.38 x 10⁶ (0.86%)	$9.74 x 10⁸ (100%)
Open surgery	$1.65 x 10⁹ (97.15%)	$2.22 x 10⁷ (1.31%)	$1.18 x 10⁷ (0.69%)	$6.66 x 10⁶ (0.39%)	$1.97 x 10⁶ (0.12%)	$5.65 x 10⁶ (0.33%)	$1.69 x 10⁹ (100%)
MIS	$1.73 x 10⁹ (97.33%)	$2.31 x 10⁷ (1.3%)	$8.68 x 10⁶ (0.49%)	$7.38 x 10⁵ (0.04%)	$2.40 x 10⁶ (0.14%)	$1.25 x 10⁷ (0.7%)	$1.77 x 10⁹ (100%)
Endoscopic FHL transfer	$1.65 x 10⁹ (98.79%)	$7.23 x 10⁶ (0.43%)	$4.21 x 10⁶ (0.25%)	$0 (0%)	$0 (0%)	$8.9 x 10⁶ (0.53%)	$1.67 x 10⁹ (100%)

Total costs in the cohort of the reference case analysis. Costs related to re-rupture treatment do not include subsequent complications (instead, these are added to their respective columns). DVT: deep venous thrombosis. FHL: flexor hallucis longus. MIS: minimally invasive surgery. WHP: wound healing problems.

TABLE III-S8 | ICER RESULTS OF ONE-WAY SENSITIVITY ANALYSIS

OPEN SURGERY	ICER	
PARAMETER	MINIMUM	MAXIMUM
New patient visits	128 766 $	128 766 $
Conservative treatment, established patient office visits	-42 977 $	183 275 $
Surgical treatments, established patient office visits	110 963 $	321 724 $
Minor WHP, additional established patient office visits	127 804 $	131 366 $
Major WHP, additional established patient office visits	128 725 $	129 151 $
Sural nerve injury, additional established patient office visits	128 696 $	129 347 $
DVT, additional established patient office visits	127 651 $	128 837 $
Magnetic resonance imaging	128 124 $	129 408 $
Doppler Ultrasound	128 715 $	128 817 $
Splint	128 766 $	128 766 $
Functional brace	128 766 $	128 766 $
Percutaneous repair jig	128 766 $	128 766 $
Interference screw	128 766 $	128 766 $
Conservative treatment, cost of rehabilitation	-154 684 $	151 738 $
Surgical treatments, cost of rehabilitation	114 993 $	400 436 $
Surgery A	85 158 $	168 085 $
Surgery B	128 766 $	128 766 $
Revision surgery	127 104 $	130 428 $
Wound care in office	128 442 $	139 329 $
Wound debridement in OR	128 643 $	129 604 $
Primary closure, skin grafting, or flap surgery	128 613 $	128 867 $
Anesthesia A	124 891 $	132 641 $
Anesthesia B	128 766 $	128 766 $
Anesthesia C	128 734 $	128 958 $
Oral ciprofloxacin 750 mg	128 761 $	128 801 $
Vancomycin 1 g IV	128 759 $	128 793 $
Gabapentin 300 mg	128 751 $	128 835 $
Rivaroxaban 15 mg	128 750 $	128 782 $
Rivaroxaban 20 mg	128 540 $	128 784 $
Conservative treatment, sick leave	-43 950 $	152 675 $

Continuation of table III-S8

OPEN SURGERY	ICER	
Surgical procedures, sick leave	102 958 $	299 583 $
Re-rupture, additional days of sick leave	116 675 $	132 095 $
Minor WHP, additional days of sick leave	128 197 $	130 873 $
Major WHP, additional days of sick leave	128 609 $	129 400 $
Re-rupture, days elapsed since primary treatment	115 376 $	141 361 $
Conservative treatment, QALYs first 3 months after injury	81 196 $	389 673 $
Conservative treatment, QALYs 3 to 6 months after injury	85 539 $	192 065 $
Conservative treatment, QALYs 6 to 24 months after injury	-4 611 471 $	21 454 308 $
Surgical treatment, QALYs first 3 months after injury	113 592 $	214 884 $
Surgical treatment, QALYs 3 to 6 months after injury	99 893 $	207 014 $
Surgical treatment, QALYs 6 to 12 months after injury	67 684 $	209 979 $

MINIMALLY INVASIVE SURGERY	ICER	
PARAMETER	MINIMUM	MAXIMUM
New patient visits	147 493 $	147 493 $
Conservative treatment, established patient office visits	-27 985 $	203 187 $
Surgical treatments, established patient office visits	129 285 $	344 830 $
Minor WHP, additional established patient office visits	146 834 $	149 273 $
Major WHP, additional established patient office visits	147 228 $	147 521 $
Sural nerve injury, additional established patient office visits	147 391 $	148 337 $
DVT, additional established patient office visits	147 384 $	149 210 $
Magnetic resonance imaging	146 845 $	148 140 $
Doppler Ultrasound	147 414 $	147 571 $
Splint	147 493 $	147 493 $
Functional brace	147 493 $	147 493 $
Percutaneous repair jig	130 954 $	149 330 $
Interference screw	147 493 $	147 493 $
Conservative treatment, cost of rehabilitation	-142 120 $	170 965 $
Surgical treatments, cost of rehabilitation	133 407 $	425 328 $
Surgery A	102 937 $	187 667 $
Surgery B	147 493 $	147 493 $
Revision surgery	145 816 $	149 169 $
Wound care in office	147 271 $	154 727 $

Continuation of table III-S8

MINIMALLY INVASIVE SURGERY	ICER	
Wound debridement in OR	146 916 $	147 577 $
Primary closure, skin grafting, or flap surgery	147 424 $	147 598 $
Anesthesia A	143 529 $	151 456 $
Anesthesia B	147 493 $	147 493 $
Anesthesia C	147 361 $	147 515 $
Oral ciprofloxacin 750 mg	147 490 $	147 517 $
Vancomycin 1 g IV	147 474 $	147 497 $
Gabapentin 300 mg	147 471 $	147 592 $
Rivaroxaban 15 mg	147 469 $	147 517 $
Rivaroxaban 20 mg	147 465 $	147 841 $
Conservative treatment, sick leave	-28 979 $	171 922 $
Surgical procedures, sick leave	121 124 $	322 024 $
Re-rupture, additional days of sick leave	135 296 $	150 851 $
Minor WHP, additional days of sick leave	147 103 $	148 936 $
Major WHP, additional days of sick leave	147 056 $	147 601 $
Re-rupture, days elapsed since primary treatment	132 275 $	161 821 $
Conservative treatment, QALYs first 3 months after injury	92 264 $	466 914 $
Conservative treatment, QALYs 3 to 6 months after injury	97 270 $	222 374 $
Conservative treatment, QALYs 6 to 24 months after injury	-9 448 228 $	7 741 651 $
Surgical treatment, QALYs first 3 months after injury	129 680 $	250 874 $
Surgical treatment, QALYs 3 to 6 months after injury	113 894 $	240 127 $
Surgical treatment, QALYs 6 to 12 months after injury	76 834 $	243 438 $

ENDOSCOPIC FHL TRANSFER	ICER	
PARAMETER	MINIMUM	MAXIMUM
New patient visits	112 107 $	112 107 $
Conservative treatment, established patient office visits	-42 861 $	161 293 $
Surgical treatments, established patient office visits	96 118 $	285 409 $
Minor WHP, additional established patient office visits	111 947 $	112 541 $
Major WHP, additional established patient office visits	111 801 $	112 140 $
Sural nerve injury, additional established patient office visits	111 611 $	112 167 $
DVT, additional established patient office visits	112 095 $	112 301 $
Magnetic resonance imaging	111 492 $	112 723 $
Doppler Ultrasound	112 099 $	112 116 $

Continuation of table III-S8

ENDOSCOPIC FHL TRANSFER	ICER	
Splint	112 107 $	112 107 $
Functional brace	112 107 $	112 107 $
Percutaneous repair jig	112 107 $	112 107 $
Interference screw	110 585 $	113 630 $
Conservative treatment, cost of rehabilitation	-143 657 $	132 836 $
Surgical treatments, cost of rehabilitation	99 738 $	356 102 $
Surgery A	112 107 $	112 107 $
Surgery B	72 759 $	147 586 $
Revision surgery	110 171 $	114 044 $
Wound care in office	112 053 $	113 870 $
Wound debridement in OR	111 441 $	112 205 $
Primary closure, skin grafting, or flap surgery	112 027 $	112 229 $
Anesthesia A	111 720 $	112 495 $
Anesthesia B	109 487 $	114 728 $
Anesthesia C	111 955 $	112 133 $
Oral ciprofloxacin 750 mg	112 107 $	112 113 $
Vancomycin 1 g IV	112 086 $	112 113 $
Gabapentin 300 mg	112 049 $	112 120 $
Rivaroxaban 15 mg	112 105 $	112 110 $
Rivaroxaban 20 mg	112 104 $	112 147 $
Conservative treatment, sick leave	-43 739 $	133 681 $
Surgical procedures, sick leave	88 820 $	266 240 $
Re-rupture, additional days of sick leave	100 507 $	115 302 $
Minor WHP, additional days of sick leave	112 013 $	112 459 $
Major WHP, additional days of sick leave	111 603 $	112 233 $
Re-rupture, days elapsed since primary treatment	100 564 $	122 917 $
Conservative treatment, QALYs first 3 months after injury	73 338 $	283 211 $
Conservative treatment, QALYs 3 to 6 months after injury	76 998 $	159 556 $
Conservative treatment, QALYs 6 to 24 months after injury	-5 792 009 $	9 960 035 $
Surgical treatment, QALYs first 3 months after injury	100 391 $	172 510 $
Surgical treatment, QALYs 3 to 6 months after injury	88 813 $	170 634 $
Surgical treatment, QALYs 6 to 12 months after injury	61 421 $	173 453 $
Probability of rerupture requiring open revision	112 107 $	113 952 $

DVT: deep venous thrombosis. FHL: flexor hallucis longus. OR: operative room. QALYs: quality-adjusted life-years. WHP: wound healing problems.

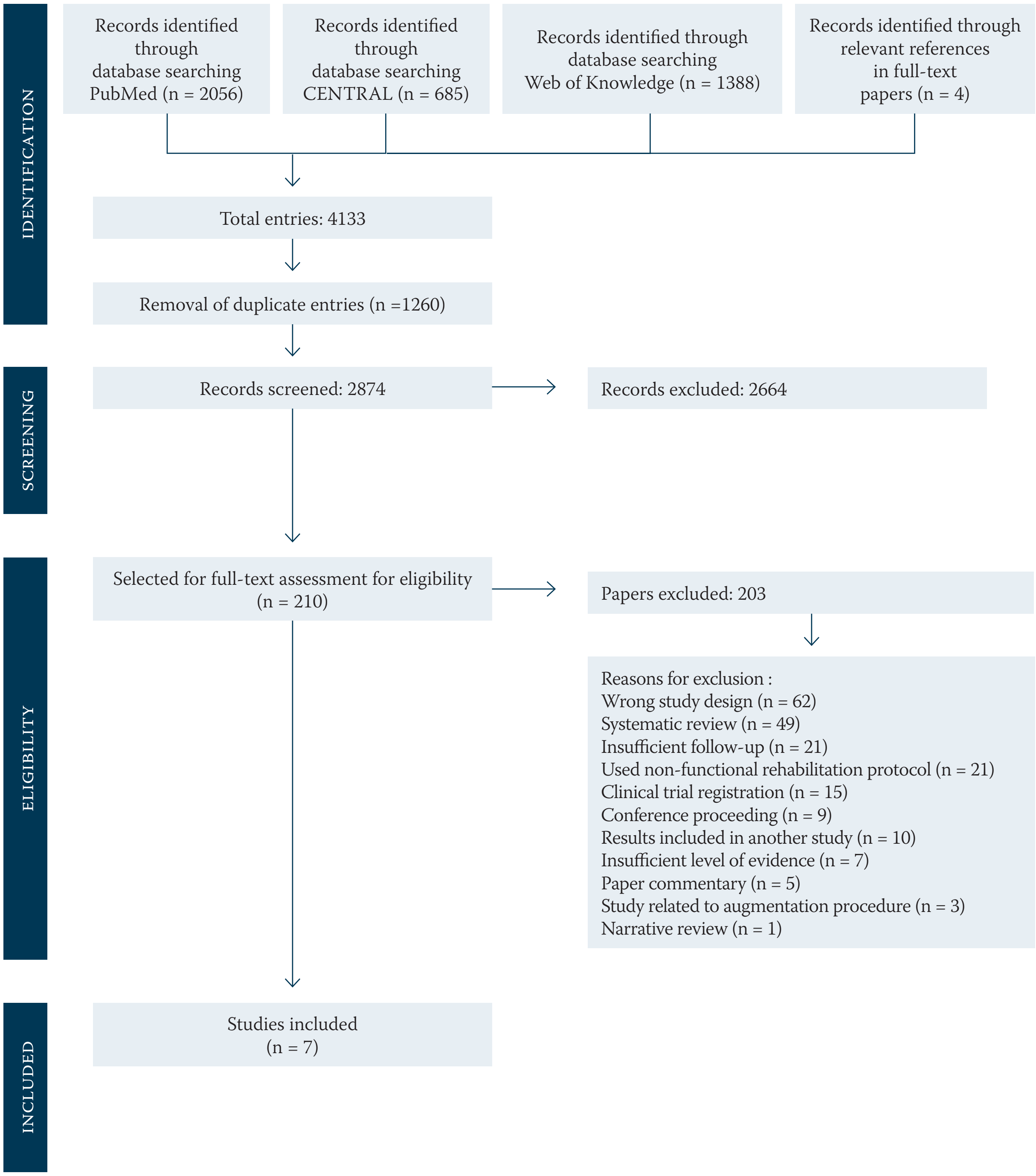


FIGURE III-S1 | Study selection flowchart with reasons for exclusion.

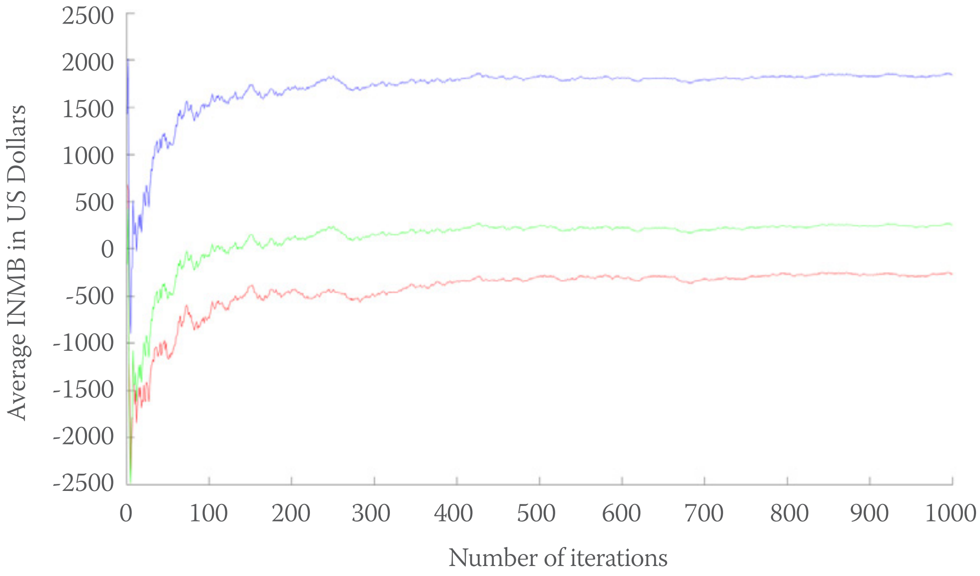


FIGURE III-S2 | CONVERGENCE PLOT FOR PROBABILISTIC SENSITIVITY ANALYSIS. This plot represents the average incremental net monetary benefit (INBM) after an *n* number of iterations for open surgery (red), minimally invasive surgery (green) and endoscopic flexor hallucis longus transfer (blue).

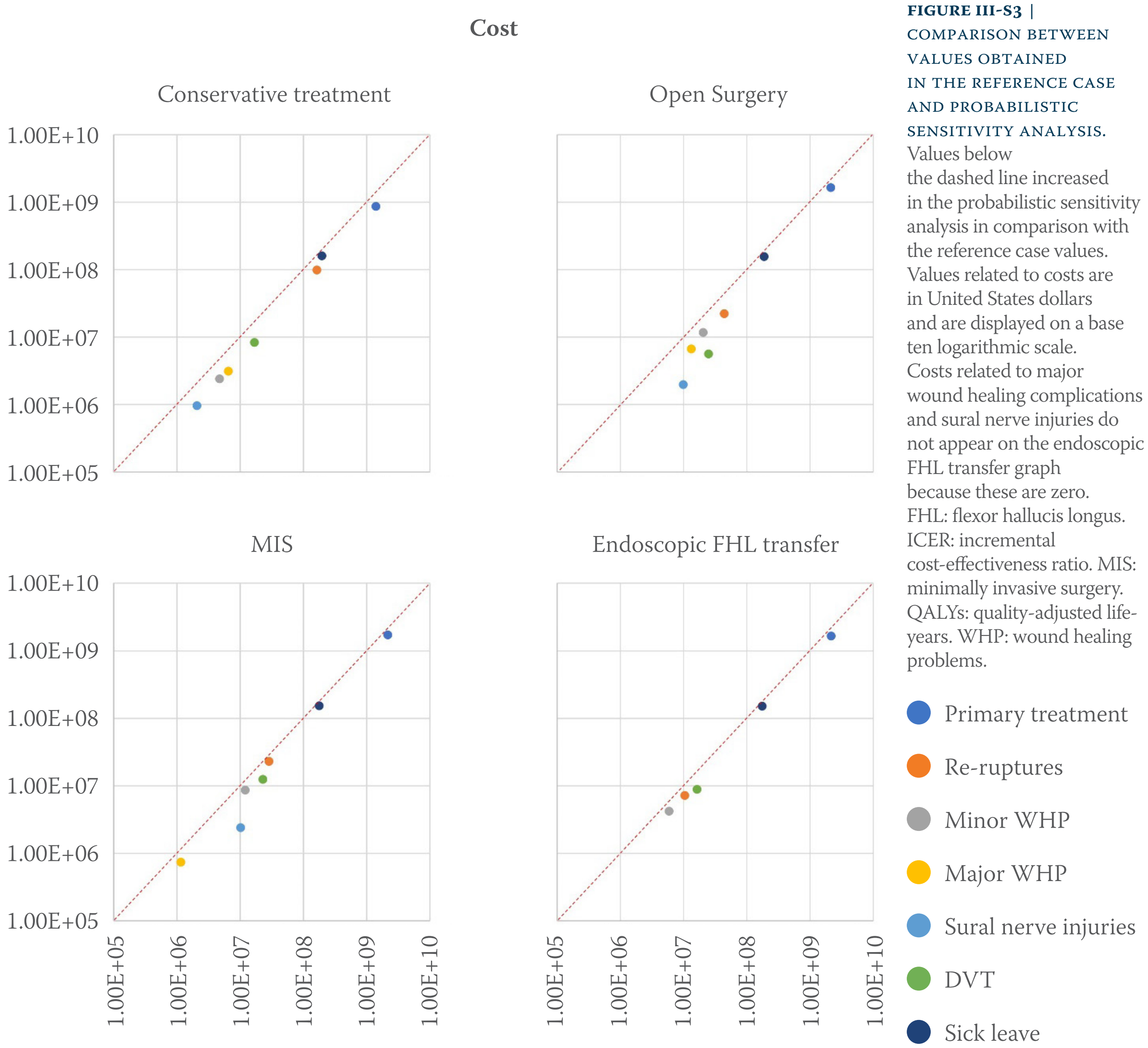
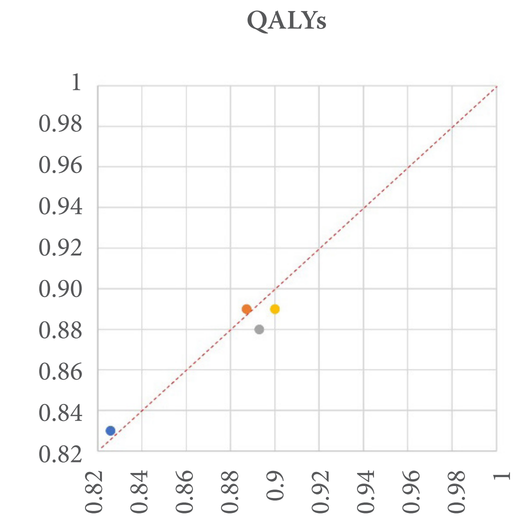
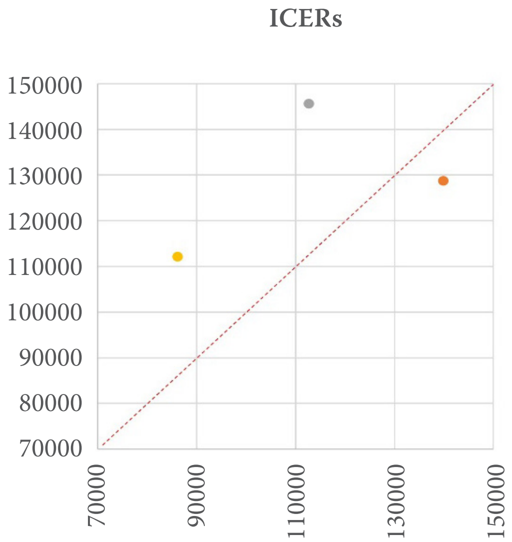


FIGURE III-S3 | COMPARISON BETWEEN VALUES OBTAINED IN THE REFERENCE CASE AND PROBABILISTIC SENSITIVITY ANALYSIS. Values below the dashed line increased in the probabilistic sensitivity analysis in comparison with the reference case values. Values related to costs are in United States dollars and are displayed on a base ten logarithmic scale. Costs related to major wound healing complications and sural nerve injuries do not appear on the endoscopic FHL transfer graph because these are zero. FHL: flexor hallucis longus. ICER: incremental cost-effectiveness ratio. MIS: minimally invasive surgery. QALYs: quality-adjusted life-years. WHP: wound healing problems.

Conservative treatment
Open surgery
MIS
Endoscopic FHL transfer



QALYs
1
0.98
0.96
0.94
0.92
0.90
0.88
0.86
0.84
0.82
0.82
0.84
0.86
0.88
0.9
0.92
0.94
0.96
0.98
1



ICERs
150000
140000
130000
120000
110000
100000
90000
80000
70000
70000
90000
110000
130000
150000

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