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Review

Imaging modalities in the diagnosis and monitoring of Achilles tendon ruptures: A systematic review

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A B S T R A C T

Objective: To determine the role of imaging in the diagnosis and monitoring of the Achilles tendon rupture (ATR).
Study design: Systematic review.
Data sources: PubMed and EMBASE in November 2016.
Eligibility criteria: Clinical studies providing information on the methods and role of imaging in the diagnosis and monitoring of the ATR were included.
Results: Fifty-six studies were included, most concerning the use of ultrasound (n = 37) or MRI (n = 18). Seven studies provided data on the diagnostic accuracy of imaging. Most ultrasound studies used a 7.5 MHz probe (19/32 studies) and scanned the patient bilaterally in prone position, with recent studies tending to use higher frequency probes (r = 0.42). Sensitivity [for detecting a rupture] ranged from 79.6 to 100%; the spread in specificity was large but two studies showed perfect (100%) data. Negative and positive likelihood ratios ranged from 0 to 0.23 and 1.0 to 10 respectively.
MRI examination was generally performed with 1.5 Tesla (T) MRI (6/12 studies) with a strong trend for higher T strength in more recent studies (r = 0.71). One study reported a sensitivity of 90.9% and one a specificity of 100%.
Although imaging can visualize structure and healing, these results were generally not related to the clinical picture. Overall, ultrasound was recommended over MRI for diagnosis and monitoring. Results of other imaging modalities remain inconclusive.
Conclusion: The adjunct role of imaging, especially of ultrasound and MRI, in the diagnosis and monitoring of ATRs was established. It is therefore recommended to rely primarily on the clinical examination and evaluation and to use imaging for ruling out other injuries and providing additional clinical information. More high-quality research is warranted into the diagnostic accuracy of imaging as well as less conventional imaging modalities' diagnostic and monitoring capabilities.

Contents

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Introduction

The Achilles tendon rupture (ATR) is a common sports injury that shows globally increasing incidence figures [1–9], that are expected to increase further, especially in the elderly, likely as a result of higher participation in recreational physical activity [10,11]. This injury significantly impairs patients with deficits persisting from 1–2 to even 10 years after injury [12,13].

Despite the increasing incidence, long-term impairment and necessary clinical procedures requiring significant time away from work/sport the treatment guidelines for ATRs are inconclusive [14], leading to possible unnecessary increased healthcare costs and an inefficient clinical protocol. Specifically the role of imaging in the diagnosis and monitoring of ATRs is not substantiated [14].

Given that misdiagnosis of ATRs delays treatment leading to chronicity and more (functional) morbidity [15], efficient diagnosis is essential. Currently, clinicians tend to rely on functional tests (e.g. the Thompson test) for diagnosis; imaging (ultrasound and MRI) is said to be reserved for the "difficult patient" [16,17]. Additionally, conservative (non-surgical) treatment is becoming increasingly common and clinicians now place a greater emphasis on early weight-bearing [7,9,18]. Imaging could have a larger role in predicting and preventing the most significant complications, re-ruptures and wound infections, during the recovery phase [19]. Despite this, the role of imaging in monitoring the increasingly emphasized rehabilitation phase is unknown [20,21].

Hence, the aim of this systematic review study was to determine the role of imaging in both the diagnosis and monitoring of the ATR. This review determined how imaging is used in ATR patients, its (additional) value in the diagnosis and/or monitoring, and strived to gain insight into the relationship between imaging and the clinical picture. Additionally, diagnostic accuracy measures were determined for the available imaging modalities to objectify the diagnostic role of imaging.

Methods

This systematic review was conducted according to the Preferred Reporting Items for Systematic reviews and Meta-Analyses protocols (PRISMA-P) [22].

Search strategy

A systematic electronic search of PubMed and EMBASE was conducted on all studies, published between 1995 in November 2016, and providing information on the role of imaging in diagnosing and monitoring ATRs. Implementation and validation of the search and search methods was attained from a Medical Librarian at the University Medical Center Groningen (see the Appendix for the complete search string). All records were imported into Refworks (ProQuest, Bethesda, MD). Backward citation tracking was performed on all included articles.

Inclusion criteria and procedure

Clinical studies assessing imaging techniques in either the diagnosis and/or monitoring (of treatment) of complete ATRs were considered eligible. Studies were only included if they provided information on the methodology of imaging examination and/or provided imaging-specific outcomes. Only studies written in English, Dutch or German languages were included. This review excluded studies focusing on the use of imaging during or as a part of treatment. Case-studies, abstracts, reviews, editorials and animal-studies were excluded.

Three reviewers were involved in the study selection process. Two reviewers (OCD and JZ) independently selected the studies in three successive rounds. First the specified criteria were applied to the titles, then the abstracts and finally the full texts. In case of uncertainty a study proceeded to the next round. Disagreement was resolved by consensus, and if agreement was not achieved, a third reviewer (IHFR) was consulted.

Data extraction and analysis

The following data were extracted from the full texts of the included studies:

Study information: year and first author(s), study design.

Methodology: patient characteristics and number, follow-up, injury and treatment applied, imaging methods and settings.

Outcomes: recommendation for imaging in diagnosis and/or monitoring, (changes in) tendon structure on imaging after injury and differences depending on treatment, association of imaging with other outcomes.

Studies comparing ATR diagnostic data to a reference standard (intraoperative confirmation) were included in diagnostic accuracy calculations. Data required to calculate sensitivity/specificity and positive/negative likelihood ratios (LR+/LR−) were extracted. One author (OCD) extracted data from the included studies. Extracted data was verified by a second author (JZ).

Methodological quality assessment

All studies were assessed for methodological quality using the Downs and Black (D&B) checklist for randomized and non-randomized studies [23]. The original checklist contains 27 questions amounting to a maximum of 32 points. We modified the scale to a maximum of 28 points, scoring the (final) question concerning power (sample size calculation) at either 0 or 1 point. This is in line with previous studies [24].

The risk of bias and applicability of the articles regarding diagnostic accuracy was scored independently by two of the authors (IHFR and OCD) using the Quality Assessment of Diagnostic Accuracy Studies Version 2 (QUADAS-2) scoring guide [25]. Disagreement was resolved by consensus.

Statistical methods

The sensitivity and specificity as well as the LR+ and LR- of articles presenting diagnostic accuracy data were calculated. True negative findings were defined as surgically confirmed partial ruptures or any other injury. LR+ greater than 10 or LR− less than 0.1 were interpreted as substantial benchmark measures for diagnostically ruling ATRs out or in [26].

To assess the settings and capabilities of imaging methods over time, a Spearman's correlation coefficient was calculated between both the frequency (MHz) of ultrasound machines and/or MR strength (Tesla) of MRI, and the difference (in years) between the year of the study and 1995. Correlation coefficients were interpreted according to Domholdt [27]. Data were analyzed using the IBM SPSS Statistics for Windows software (Version 23.0, Armonk, NY: IBM Corp.).

Results

Search results

The applied search string yielded 1781 articles (Fig. 1). Of these articles 54 met our inclusion criteria and 2 were included after backward citation tracking, yielding a total of 56 included studies. Tables 1–4 show the extracted data and methodological quality of the included studies. Thirty-seven studies concerned ultrasound [28–64], eighteen MRI [30,54,58,65–78], and nine concerned X-ray, CT, Optical Coherence Tomography (OCT) Roentgen Stereophotogammic Analysis (RSA), Diffusion Tensor Imaging (DTI), Fluorodeoxyglucose-Positron Emission Tomography (FDG/PET), or CT [31,38,47,76,79–83]. Nine studies utilized multiple imaging modalities [30,31,38,47,49,54,58,81,82]. Seven studies [41–43,52,56,66,69] met the criteria for diagnostic accuracy calculations and Table 4, Figs. 2 and 3 show the characteristics, sensitivity and specificity and QUADAS-2 appraisal respectively.

Ultrasound

The mean D&B score of ultrasound studies was 16.4 (SD = 3.99).

The studies that applied ultrasound referred to a transducer in the range of 5–20 MHz [28–45,48,49,51–54,56–64], with specifically 7.5 MHz being the most frequently chosen frequency

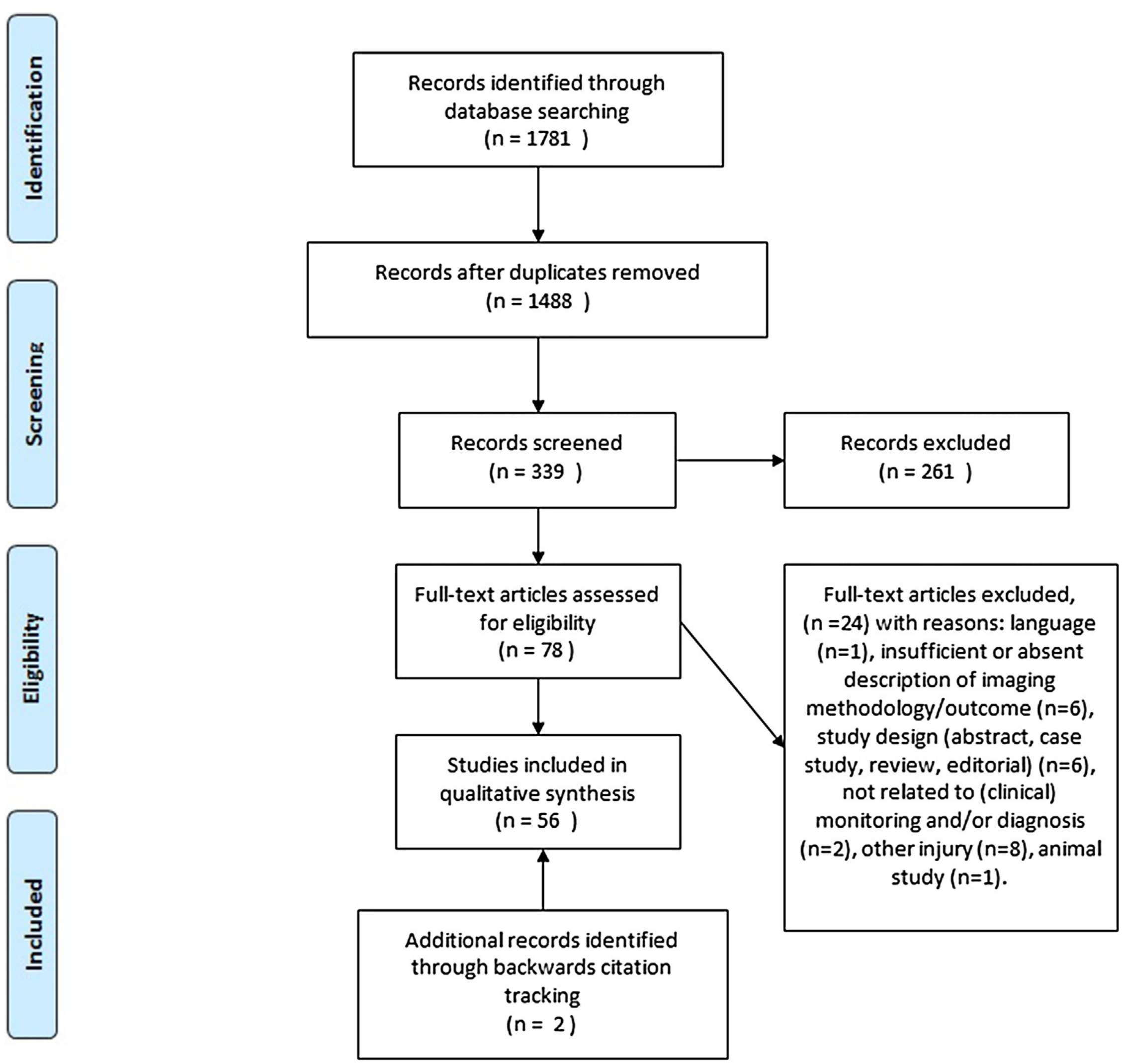

Fig. 1. Search string and data selection results.

Table 1
Studies concerning diagnostic and monitoring data: ultrasound.

Studies	Design	N	Pathology + Analysis	Imaging	Follow-Up	Imaging Characteristics	Outcomes and Conclusions	D&B Score
Agres et al. [28]	Prospective cohort	20	Achilles tendon rupture surgically treated. Ultrasound, dynamometry and gait analysis	Ultrasound	2–6 years after surgical repair	B-mode ultrasonography with a 7.5 MHz probe. Previously injured and contralateral limbs were imaged.	Injured tendons were stiffer and had greater rest length. Tendon stiffness correlated with altered maximum plantarflexion moment during gait ($r = -0.509$).	14
Amlang et al. [29]	Cross-sectional	273	Achilles tendon rupture. 226 “fresh” ruptures, 47 “outdated”. Ultrasound used to determine type of rupture	Ultrasound	Single scan	7.5 MHz, prone position, 20° plantarflexion, dynamic examination for proof of injury.	Ultrasound reliable for differentiation into rupture type (partial or complete). Useful for treatment selection.	18
Blankstein et al. [31]	Prospective cohort	20	Complete rupture, surgically treated patients	Ultrasound	Ultrasound for diagnosis (n = 20), intraoperative evaluation (n = 5), and immediate postoperative (n = 15) and follow-up at 6 months	5–13 MHz, bilateral examination.	Intra and postoperative ultrasound comparison beneficial. Ultrasound can guide treatment. Tendon thicker at 6 months.	16
Bleakney et al. [33]	Prospective cohort	70	Achilles tendon rupture, surgically and conservatively treated patients	Ultrasound	Average of 63 months	Bilateral examination, 7.5 MHz, patient prone feet over table, longitudinal and transverse planes.	Ultrasound little correlation with pathology and function/pain. Ultrasound shows long term differences in structure, possibly representing tendinopathic background. No difference in tendon structure depending on treatment. Recommendation: dynamic, more than one plane ultrasound.	21
Busilacchi et al. [34]	Prospective cohort	25	Spontaneous rupture, surgically treated, 60 control tendons scanned to determine normal elastographic range	Ultrasound + sonoelastography	40 days, 6 months and 1 year	Ultrasound with B-mode function (5–12 MHz). Patient prone, both ankles over bed. Bilateral examination. Elastogram superimposed after ultrasound.	Thickness increased in both tendons. Stiffness increased in both tendons, contralateral tendon increased in stiffness over time. Inverse correlation between subjective outcome and stiffness ($r = -0.42$).	24
Chen et al. [35]	Prospective cohort	14	14 Achilles tendon ruptures, 36 controls	Ultrasound + shear wave elastography	2 ruptures in “healing stage”, 12 ruptures within 24 h	Real-time supersonic shear wave elastography coupled with a linear array transducer (4–15 MHz) used to assess the elasticity of the Achilles tendons. Each tendon was scanned in a prone position with the foot hanging over the edge of the examination bed in a neutral position.	The anatomic structure of the ruptured tendons was easy to distinguish on the elasticity map. The elasticity values of the normal tendons were significantly higher than the ruptured ones. Elastography provides more functional information following healing; helps to optimize treatment following functional rehabilitation.	14
Chillemi et al. [36]	Prospective cohort	38	Post-surgery ruptures. 35 complete, 3 partial. 37 patients completed one-year follow-up	Ultrasound	5, 24, 48 weeks	Prone, feet over table, ankles neutral, 7.5 MHz probe, injured and uninjured tendon, longitudinal and transverse planes.	Ultrasound confirmed diagnosis after Thompson test in some patients. Ultrasound valuable as diagnostic/prognostic	17

Table 1 (*Continued*)

Studies	Design	N	Pathology + Analysis	Imaging	Follow-Up	Imaging Characteristics	Outcomes and Conclusions	D&B Score
							imaging. Ultrasound shows abnormalities and healing up to 48 weeks post-surgery.	
Coutts et al. [37]	Prospective cohort	25	Achilles tendon rupture, 21 ultrasound scans, surgically treated patients	Ultrasound	Mean: 3.4 years (range: 6 months–9.25 years	7.5 MHz patient prone, feet hanging over table, neutral, longitudinal and transverse planes. Bilateral examination.	Injured tendons were thicker. Ultrasound abnormalities post-surgery not associated with clinical picture.	16
Genovese et al. [39]	Prospective cohort	14	14 with history of Achilles tendon ruptures surgically treated, 10 controls	Ultrasound, Doppler and contrast-enhanced ultrasound	Single scan within 2 years post-rupture	Patient prone, ankle at 90°, 13–14 MHz longitudinal.	Recommendation: no Doppler immediately after activity (more blood flow), Doppler signal not indicative of disease, contrast ultrasound more sensitive than Doppler for revascularization.	15
Geremia et al. [40]	Prospective cohort	18	18 with previous Achilles tendon rupture (comparison early mobilized and immobilized), 9 healthy controls	Ultrasound	Single scan 2 years after injury	Linear probe, 7.5 MHz, ultrasound probe was placed perpendicular to the tendon and three transverse images were obtained at 2 cm, 4 cm, and 6 cm from the tendon's insertion on the calcaneus.	Two years post-surgical repair, the ruptured Achilles tendon mechanical and structural properties (CSA, length, force stress-strain) differ from uninjured. Injured tendon is more compliant. Patients' uninjured tendons were similar to controls.	19
Hollenberg et al. [44]	Prospective cohort	11	Achilles tendon rupture, conservative treatment	Ultrasound + Doppler	Initial scan within 48 h. Follow-up at mean 22.4 months (range: 7–38 months)	Injured and contralateral tendon, 7.5 MHz, patient prone, dynamic examination.	Ultrasound to confirm diagnosis. The ATR treated non-operatively has a different sonographic appearance than healthy or acutely ruptured tendon.	10
Hufner et al. [45]	Prospective cohort	168	Achilles tendon rupture. Ultrasound + follow up 125 (patients for follow-up). Conservatively treated patients	Ultrasound	Initial scan for treatment selection. Follow-up at 4, 8, and 12 weeks	7.5 MHz, patient prone, plantarflexion	Ultrasound can select patients for non-operative treatment by measuring gap. Injured tendon thicker. Little correlation between ultrasound and functional outcome.	10
Hutchison et al. [46]	Prospective cohort	273	Specialized protocol for Achilles tendon rupture patients. 211 managed conservatively, 63 surgically. Patients scanned within 2 weeks of injury	Ultrasound	4, 6, and 9 months	Flex and extend the knee during examination, and assess the amount of opposition of tendon ends in varying degrees of equinus. Dynamic plantarflexion of foot.	Ultrasound used for diagnosis to determine site and extent of rupture and gap size. Routine ultrasound proves cost-effective (less unnecessary surgical interventions).	17
Kainberger et al. [48]	Retrospective cross-sectional	52	Tendonitis, heel-swelling or suspected ruptures. 8 ruptures. Ultrasound findings used to correlate with final diagnosis	Ultrasound		5–10 MHz, transverse and sagittal planes, dynamic examination.	Ultrasound signs not specific for each of the diagnoses. Discrepancy between symptoms and ultrasound signs. Ultrasound for diagnosis and to define extent of disease.	22
Kotnis et al. [50]	Cross-sectional	125	Achilles tendon rupture, both surgical and conservative patients	Ultrasound	Ultrasound within 7 days of injury	Foot in resting position then moved to plantarflexion, comparison made between gap.	Ultrasound used for treatment selection based on gap size can reduce re rupture.	21
Majewski et al. [51]	Prospective cohort	73	Achilles tendon ruptures, both	Ultrasound		7.5 MHz neutral, patient on stomach.	No correlation between echo	15

Table 1 (*Continued*)

Studies	Design	N	Pathology + Analysis	Imaging	Follow-Up	Imaging Characteristics	Outcomes and Conclusions	D&B Score
			surgically and conservatively treated patients		4, 8, 12 and 26 weeks and 2.5 years		structure and tendon functionality. Ultrasound cannot study quality of healing and relation to function, only stage. No difference between healing structure in surgical and conservative patients.	
Merk et al. [53]	Prospective cohort	54	Achilles tendon rupture, surgically treated patients	Ultrasound	Average 4.4 years	7.5 MHz foot over exam table compare to healthy contralateral tendon, longitudinal and transverse planes.	No correlation between Ultrasound abnormalities and clinical results.	13
Ofer et al. [55]	Prospective cohort	9	8 degenerative and 1 traumatic rupture, surgically. 9 controls.	Ultrasound (motion analysis)	Single scan, 2–9 months post-rupture	Motion analysis ultrasound. Dorsiflexion to plantarflexion with linear transducer. Bilateral examination.	Negative asymmetry higher in dorsiflexion phase of degenerative but not in traumatic rupture post-operatively. Ultrasound to guide degenerative change of contralateral tendon.	13
Qureshi et al. [57]	Prospective cohort	26	Confirmed Achilles tendon rupture by clinical picture and ultrasound	Ultrasound	Single scan within a week of injury	Prone, 12 MHz linear transducer, axial/sagittal planes. The gap distance was sequentially measured with the foot in maximum ankle equinus and the knee in 0°, 30°, 60°, and 90° of flexion.	Ultrasound used to confirm diagnosis. Tendon edge apposition following acute Achilles tendon rupture is dependent on both knee flexion and foot position. Ultrasound can identify patients who benefit most from surgery/at risk of re-rupture.	20
Rupp et al. [59]	Prospective cohort	60	Post-surgery Achilles tendon rupture	Ultrasound	Single scan at a mean of 11 years (range 2–19)	Injured and contralateral tendon, 7.5 MHz, patient prone and feet 10° dorsiextension	No correlation between ultrasound and clinical outcome, although ultrasound does show long-lasting alterations.	10
Suydam et al. [60]	Prospective cohort	4	4 patients with Achilles tendon rupture, surgically treated, 5 healthy controls.	Ultrasound and motion analysis via EMG	6 and 12 months	Bilateral examination. Patient prone, foot hanging off the edge of the table. B-mode 10 MHz ultrasound used to determine length	Tendon length increased. Moderate correlation between EMG of lateral gastrocnemius and tendon length (r = 0.52). Slight correlation with medial gastrocnemius (r = 0.38).	12
Tan et al. [61]	Prospective cohort	16	19 surgically repaired tendons compared to 40 asymptomatic tendons of 20 controls	Ultrasound + sonoelastography	Median: 36.8 months (range 4–180 months)	Ultrasound examination with a real-time sonoelastographic scanner at a frequency range of 5–13 MHz The Achilles tendons were examined axially and longitudinally while the patient was lying in the prone position with the foot hanging over the edge of the examination table in a relaxed position.	Elasticity and thickness values did not differ based on portion of tendon. In all patients with complete ruptures, heterogeneous and stiff-type alterations were identified with real-time sonoelastography, this differed from controls. Conclusion: despite changes mean American Orthopedic Foot and Ankle Score (AOFAS) score was excellent.	17

Table 1 (*Continued*)

Studies	Design	N	Pathology + Analysis	Imaging	Follow-Up	Imaging Characteristics	Outcomes and Conclusions	D&B Score
Vadala et al. [62]	Retrospective cohort	80	Surgically treated subcutaneous rupture patients. <40 years old	Ultrasound + power Doppler	Single scan at a mean of 58 months (range 26–116)	Linear multifrequency (7.5–12 MHz). Examination of both tendons in longitudinal and transverse planes. Doppler to display neovascularization.	Ultrasound showed larger tendon. Tendon structure remained irregular in most patients. Most patients showed no neovascularization.	19
Westin et al. [63]	Prospective cohort	45	Ultrasound of patients participating in RCT comparing surgical and nonsurgical treatment. Ultrasound to measure diastasis	Ultrasound	Ultrasound performed within 72 h of injury, clinical and functional follow-up at 12 months	13.5 MHz multifrequency linear array transducer, using an 11.4-mHz default setting and scanning parameters aimed for superficial musculoskeletal scanning. Scanning of the Achilles tendon was performed in both longitudinal and axial planes assisted by dynamic scanning during passive ankle motion.	Patients with a larger initial gap-size on ultrasound had a higher degree of re-rupture. Ultrasound useful in predicting re-rupture, and assessing surgical indication. Ultrasound should not be used as a diagnostic tool due to the occurrence of false negatives.	21
Zhang et al. [64]	Prospective cohort	26	Ultrasound + shear wave elastography of surgically treated patients	Ultrasound + shear wave elastography	12, 24, 48 weeks post-operatively	Linear array transducer (4–15 MHz) was used to assess the elasticity of the Achilles tendons. Each tendon was scanned in a prone position with the foot hanging over the edge of the examination bed in a neutral position.	Mean elasticity values were different for repaired tendons. Elasticity values correlated with functional outcomes (odds ratio = 0.92). US can detect postoperative stiffness (this value gradually increased).	16

[28,29,31,33,36,37,40,43–45,49,51–54,56,58,59,62] (19/32 articles). The frequency of probes increased moderately in more recent articles (r = 0.42). One study [41] concluded more MHz resulted in more clarity and was excluded from frequency vs. time analysis for this reason.

The applied examination protocol varied per study. The general guideline consisted of the patient lying prone with their foot hanging over the table (neutral) [29,30,33–37,39,42–45,47,49,51–53,56,57,59–61,64] and an ultrasound being made of both the injured and (healthy) contralateral tendon [28,31–34,36,37,41,42,44,47,49,52–56,58–60,62]. The longitudinal and/or transverse planes were mostly referenced to [33,36,37,39,43,48,49,52–54,56,61–63], although some studies reported analyzing axial and/or sagittal planes [48,54,57,58,61,63]. Most studies examined the tendon dynamically [29–31,33,42,44,46,48,50,52,55,57,58,63], four studies performed the examination with the foot in plantarflexion [39,45,57,59].

Studies examining ultrasound's diagnostic role in patients with Achilles tendon pain recommended its use. Only one study [63] discouraged the use of ultrasound due to the occurrence of false negatives. Ultrasound is said to determine the type (full, partial or even plantaris tendon) and level of rupture, define the extent of tissue damage and prognosis as well as aid in providing an indication for treatment selection (surgery or (type of) conservative treatment) [29–32,36,41–46,48,50,52,56,57,63]. In avoiding diagnostic pitfalls, it is stated that tendon edge apposition is dependent on knee flexion and foot position [45,46,50,57] and recommended ultrasound be performed dynamically, in more than one plane, and not immediately post-activity, due to possible increased blood flow [31,33,39].

In terms of its monitoring potential, the results and conclusions of the studies revealed that ultrasound results show various pathological changes after ATR treatment [28,32–38,40,44–47,49,51–55,58,60–62,64]. Combining elastography with ultrasound analysis showed post-ruptured Achilles tendons are stiffer and have a higher elasticity and more heterogeneous structure [34,35,61,64]. In addition, ATRs show (long term) changes in mechanics (force/strain and stiffness) [28,34,40], area [40,47] and flow on Power Doppler ultrasound (PDUS) [38]. The studies confirmed that ultrasound can detect healing and guide decisions after primary treatment and during rehabilitation [32,35,46,55,57,58,63], provide prognostic information [36,48,57,63], reduce re-rupture incidence [50,57,63] and detect degenerative change in the contralateral tendon [34,55]. No difference was found in tendon structure depending on treatment (surgical or conservative) from 4 weeks to 63 months [33,51,54]. Despite the articles' recommendation for ultrasound, the pathology detected is not associated with clinical or functional deficits. There seemed to be little to no association between tendon structure on ultrasound and tendon function post-treatment [33,37,39,45,51,53,54,59,61]. Rominger et al. [58] and Margetic et al. [52] found a significant positive correlation between ultrasound abnormalities and the patient's clinical picture and functional recovery. Agres et al. [28] determined tendon stiffness had a moderate negative correlation with altered gait and Suydam et al. [60] found a moderate correlation between tendon length on ultrasound and compensatory muscle activation (triceps surae)

Table 2
Studies concerning diagnostic and monitoring data: MRI.

Studies	Design	N	Pathology + Analysis	Imaging	Follow-Up	Imaging Characteristics	Outcomes and Conclusions	D&B Score
Fujikawa et al. [65]	Prospective cohort	39	40 acute Achilles tendon ruptures surgically repaired (open (n = 10) or percutaneous (n = 30))	MRI	4, 8, 12 weeks	1.5 T. Supine at MRI, injured tendon in coil. Axial T1 and axial/sagittal T1/T2 images.	Earlier disappearance tendon gap on T2 and in open surgery group. MRI can visualize normal healing.	15
Haims et al. [67]	Retrospective cross-sectional	88	Wide-array of Achilles tendon abnormalities, 94 feet with "abnormal" MR examinations were retrospectively evaluated and clinically correlated. 36% had Achilles tendon tears, 13% complete tears	MRI	Patients who had been symptomatic ranging from 1 day to 3 years	1.5 T MRI. T1/T2. Patients imaged in an extremity coil, sagittal/axial analysis.	Thicker tendons associated with tears. T2 signal did not distinguish symptomatic from asymptomatic, however greater increase in T2 with pathology. Hard to correlate MRI with symptoms.	14
Karjalainen et al. [68]	Prospective cohort	20	21 complete surgically treated ruptures	MRI	3 and 6 weeks and 3 and 6 months post-surgery, preoperative diagnostic MRI of 2 patients	0.1 T MRI. At 3 weeks patient supine, T1 and T2 sagittal, T2 in axial plane. Contralateral tendon evaluated as well.	Thickness of tendon increased most between 6 weeks and 3 months. At 3 weeks tendon best seen at T2 sagittal. At 6 weeks T2 weighted images best. MRI poor at predicting ATR. MRI correlates with functional capacity at 3 (r = −0.50–0.66) and 6 months (r = −0.50–0.60. MRI can assess structure.	20
MacMahon et al. [70]	Case-control	21	MRI of 50 healthy and 21 ruptured patients. Determination of tendon rotation and distance to sural nerve	MRI	Date of rupture available for 6 subjects, mean 6 days after injury	Foot positioned neutral, without excessive plantar or dorsiflexion, in an extremity coil. Four image acquisitions were obtained, including a sagittal inversion recovery.	Ruptured Achilles tendons showed greater external rotation at the ankle not more proximal to the insertion. Proximal tendon rotation correlated with rupture height. The sural nerve was closer anteriorly and farther laterally in ruptures (likely due to swelling/rotation). Achilles tendon was thicker in ruptured cohort.	19
Maffulli et al. [71]	Prospective cohort	16	Post-surgery Achilles tendon rupture	MRI	Average 32.5 months (range 29–36 months)	1 T MRI of operated and non-operated tendon, supine, feet first, ankle held plantigrade at 90° flexion. Proton density and T2 weighted images.	Operated tendons significantly thicker. Possible non pathological MRI abnormalities post-surgery not necessarily of significance.	20
Rebeccato et al. [72]	Retrospective cohort	52	Achilles tendon rupture surgically treated	MRI	Minimum 12 months, MRI of 40 patients.	T1 and T2 weighted images, Achilles tendons and calf muscle were analyzed. Axial and sagittal planes.	MRI reveals enlargement of operated tendon. Possible relationship between muscle compartment area on MRI and subjective outcome, as they decreased similarly.	19
Rosso et al. [73]	Retrospective cohort	52	Achilles tendon rupture, conservative and surgical treatment	MRI	Patients contacted after three years. Mean: 91 months	3 T MRI. Injured and contralateral tendon, supine, ankle dorsiflexed at 90°. T1 in coronal plane, axial fat-saturated T2 and axial T1.	Muscle volume and tendon length difference in injured and uninjured. No differences in treatment groups. CSA correlated with muscle volume. Muscle volume did not correlate with Achilles Tendon Rupture Score (ATRS) or tendon length and only to a slight degree with Hannover score. Concluded that ultrasonography is cheaper, less time consuming for follow-up.	18
Sadek et al. [74]	Prospective cohort	18	Patients with chronic ruptures and defects >5 cm, surgically treated	MRI	1 week preoperatively and 4, 8, 12 weeks post operatively	1.5 T MRI. During MRI, the patient lay in the supine position with the affected Achilles tendon placed on the coil. The protocols were sagittal and axial fat-suppressed spin-echo T1-weighted images axial, and sagittal fast spin-echo T2-weighted images.	MRI used to confirm diagnosis. Achilles tendon healing and tendon gap disappearance perceived with higher sensitivity in T2-weighted images than T1. MRI tendon gap gradually disappeared.	14

Table 2 (*Continued*)

Studies	Design	N	Pathology + Analysis	Imaging	Follow-Up	Imaging Characteristics	Outcomes and Conclusions	D&B Score
Sarman et al. [75]	Retrospective cohort	45	Surgically treated patients	MRI	9 months after surgery	1.5 T MRI. The patient was placed supine position and the leg at rest. The MRI protocol included axial, sagittal, coronal T1-weighted turbo-spin echo, axial proton density-weighted, coronal T2-weighted turbo-spin echo, and coronal short T1-weighted inversion recovery sequences.	The operated sides were significantly thicker than the healthy sides at 9 months.	14
Wagnon et al. [77]	Prospective cohort	57	Post-operative Achilles tendon ruptures (n = 35 open repair, n = 22 percutaneous)	MRI	Operation within 2 weeks, single post-operative MRI of 40 patients, average follow-up of 40 months (range 12–105 months)	Bilateral examination consistent with Rebecatto et al. [72]	Operated tendon thicker. MRI images difficult to correlate with functional results; should be used in difficult cases.	17
Yasuda et al. [78]	Prospective cohort	30	30 chronic (>4 week old) rupture patients surgically treated. Pre and post-operative MRI	MRI	MRI preoperative and at 3 and 6 months	1.5 T MRI, T1/T2 weighted images in the axial and sagittal planes.	MRI can detect changes preoperatively and postoperatively (larger tendon). Thickening seen on T2. MRI used to assess healing.	20

after ATR. Four studies [34,35,61,64] combined ultrasound with elastography, one determining elasticity values had a very strong positive correlation with functional outcome [64], one showing a moderate inverse correlation between stiffness and subjective outcome [34] and another that elastography provides additional functional data [35]. The other articles were unanimous that ultrasound can define pathology and herewith the possible stage of tendon healing; this does not show an association with function.

MRI

The mean D&B score of MRI studies was 16.6 (SD = 3.2).

The MRI studies used T1/T2 weighted images. Half (6/12) of the studies referring to Tesla (T) strength of MRI used a 1.5T machine [30,49,54,65,67,68,73–75,78]. There was a strong positive correlation between the year of the study and the T capabilities of MRI (r = 0.71). The general examination positioned the patient supine, placed the ankle/foot in the coil [54,65,67,68,71,73–75] and followed with acquisition of T1/T2 images [30,58,65,67,72–74,76–78] in axial and sagittal [30,54,58,65,67,68,72–76,78] and sometimes coronal [30,73,75,76] planes. Seven studies imaged the contralateral tendon [49,54,58,68,71,73,76]. Specified foot position ranged from neutral [70,75] to plantarflexion [54,71] to dorsiflexion [73].

Six studies examined MRI as a diagnostic tool [30,66,67,69,70,74]. Upon presentation ruptured tendons were thicker [67,78] and showed increased external rotation on MRI [70]. Bianchi et al. [30] determined MRI can diagnose a plantaris tendon tear but recommended ultrasound since it is faster and cheaper and Garras et al. [66] discouraged the use of MRI because it is too costly and time-consuming.

As a monitoring modality, MRI is said to visualize structure, pathology, and normal healing [49,58,65,67,68,71–75,77,78], but is said to be too time-consuming or inferior to ultrasound for routine use [54,58,71,73,77,78]. Pathology was reported to be best seen on T2-weighted images [65,67,68,74,78]. The operated tendon was stated to be thicker, more heterogeneous and more irregular [49,54,58,68,71,72,75,77,78]. Two studies assessed the tendon structure in both conservatively and operatively treated, both concluding there to be no difference after 6 months and 3 years [54,73].

There seemed to be a limited relationship between MRI signal pathology and tendon function [54,67,71–73,77]. Karjalainen et al. [68] determined a moderate positive correlation between signal pathology and functional (recovery) at 3/6 months and also presented data showing the patients with the poorest outcome had the largest intratendinous signal [49]. Rominger et al. [58] (also) found that MRI pathology positively correlated with functional capacity, and Rebeccatto et al. [72] concluded that a possible relationship between muscle compartment area on MRI and subjective outcome exists.

Other imaging modalities (X-ray, RSA, CT, OCT, FDG/PET, DTI)

The mean D&B score of studies concerning other modalities was 16.1 (SD = 5.8).

Nine studies investigated other imaging modalities than ultrasound or MRI, determining their use to be of limited value (X-ray) [31,80] or complementary (OCT) [79]. Three modalities (FDG/PET, DTI, and RSA) showed a potentially relevant relation with other recovery outcomes during ATR monitoring. FDG/PET [38] showed a strong negative correlation (r = −0.89) between tendon metabolism and subjective outcome, the diffusion coefficients calculated by DTI had a moderate positive correlation (r = 0.71) with the time patients are followed up [76] and RSA results showed a moderate correlation at 6–18 weeks (r = 0.76) and a weak correlation at 1 year (r = 0.41) with tendon function [81,83].

Diagnostic accuracy

Data on diagnostic accuracy are presented in Table 4 and Fig. 2. The sensitivity of ultrasound ranged from 79.6% to 100% [41–43,52,56]. Two ultrasound studies reported perfect (100%) specificity data [52,56]. Griffin et al. determined that performing the Thompson test during ultrasound examination (RAUT) is more sensitive and more specific than traditional (static) ultrasound [42]. The LR+ of ultrasound ranged from 1.0-10 (three studies) and LR− from 0 to 0.23 (four studies).

Table 3
Studies concerning diagnostic and monitoring data: other and combined modalities.

Studies	Design	N	Pathology + Analysis	Imaging	Follow-Up	Imaging Characteristics	Outcomes and Conclusions	D&B Score
Bagnaninchi et al. [79]	Case-control	24	Samples of 14 ruptured Achilles tendons post-surgery analysed ex-vivo compared to 10 controls (patella and tendinopathic Achilles tendons)	Polarization Sensitive Optical Coherence Tomography (PSOCT)	Scanned within 24 h post-surgery	Prior to PSOCT scanning, the samples were marked by inking the starting PSOCT scan line and scan direction for referencing with histology. PSOCT system fitted with a superluminescent diode with a central wavelength of 1310 nm and a bandwidth of 52 nm. Immediately after being scanned the tendon fibre alignment, cellularity and tenocyte nuclei were evaluated.	PSOCT is able to assess the changes that occur with spontaneous Achilles tendon rupture and with Achilles tendinopathy. PSOCT will be complementary to other techniques for the assessment of tendon pathology.	10
Bianchi et al. [30]	Retrospective case-series	5	Plantaris tendon rupture	Ultrasound + MRI	Ultrasound 8 and MRI 10.2 days after trauma	Ultrasound: prone, feet hanging over table, both sides, 12.5 or 17.5 MHz transducers. Dynamic examination. MRI: 1.5 T. Sagittal/axial/coronal T2, axial T1.	Both ultrasound and MRI distinguish Plantaris tendon from Achilles tendon tear. Recommendation: ultrasound of Plantaris tendon in patient presenting with pain.	14
Blankstein et al. [31]	Retrospective cross-sectional	41	41 with Achilles pain, 2 Achilles tendon ruptures	Ultrasound + X-ray in 1/3		Bilaterally examined by using a 5–13 MHz linear transducer at a constant frequency of 7.5 MHz. Regular X-rays were obtained in one-third of the patients, and the lateral view of the heel was reviewed for diagnostic purposes.	Ultrasonography should be applied in the primary clinic, dynamically and in real time. Compared to magnetic resonance imaging ultrasonography has the capability of demonstrating physiological movement, and is simpler and more cost effective Recommendation: ultrasound in patients with Achilles pain, aids in surgical selection.	11
Eliasson et al. [38]	Prospective cohort	23	23 patients with surgically repaired Achilles tendon rupture. Tantalum beads inserted to measure elongation. Measurement of glucose uptake, vascularization and subjective (ATRS and VISA-A) outcome	FDG/PET + power Doppler ultrasonography (PDUS)	3 (n = 7), 6 (n – 7), and 12 (n = 9) months post-surgery	FDG/PET and power Doppler ultrasonography (PDUS).	Relative glucose uptake was higher at all time-points and negatively correlated ($r = -0.89$) with ATRS at 6 months after repair. PDUS flow activity was higher in repaired tendons than in intact tendons at 3 and 6 months, but normalized by 12 months. There is a negative correlation between tendon metabolism and PROM's, metabolic activity can be increased for up to a year despite normal vascularization.	11
Jielile et al. [47]	Prospective randomized trial	57	Randomized comparison of early post-operative rehabilitation with post-operative cast immobilization for neglected Achilles tendon rupture	Ultrasound + Multislice spiral computerized tomography	8, 12, 18, 26 weeks and 2 years	Ultrasonographic measurement of the cross-sectional area in both the healthy side and the ruptured side of the tendon performed using color Doppler with the patients lying in prone position on the testing bed and the ankle in a neutral position. Multislice spiral CT scanning of the ankle	The cross-sectional area of the ruptured side of the tendon was much larger than that of the healthy side (more for early post-operative rehabilitation).	24

Table 3 (*Continued*)

Studies	Design	N	Pathology + Analysis	Imaging	Follow-Up	Imaging Characteristics	Outcomes and Conclusions	D&B Score
						with the same measurement protocol.		
Karjalainen et al. [49]	Prospective cohort	13	Surgically treated Achilles tendon ruptures, male patients. 9 with uninjured contralateral tendon available for bilateral examination	MRI + ultrasound	Average time from surgery to imaging was 17.7 months (range 12–36 months)	Ultrasound: patient placed prone, with feet hanging free. Linear 7.5 MHz transducer. Transverse and longitudinal images, contralateral tendon imaged as well. MRI: 0.1 T. T1 and T2. Both tendons imaged.	MRI showed more rounded and irregular contour of injured tendon. Ruptured tendon was larger on ultrasound and delineated less sharply. Only MRI showed intratendinous lesion. Two patients with the largest intratendinous lesions had poor clinical outcome.	16
Moller et al. [54]	Prospective randomized trial	58	Achilles tendon rupture, surgically and conservatively treated in randomized trial	Ultrasound + MRI	Ultrasound at 6, 12 and 24 months. MRI at 12 months	Ultrasound: 7.5 MHz, scanning of both tendons, longitudinal and axial planes.	Tendon was thicker and more heterogeneous at 1 year. No correlation between imaging and subjective or functional parameters at 1 year. No difference in structure (except for gliding function) depending on treatment.	22
						MRI: 1 T. Both tendons scanned separately. Supine, feet slightly plantarflexed in coil. Axial and sagittal planes, T2.	Conclusion: post-treatment ultrasound or MRI of limited value. Partial defects visible in higher number on ultrasound.	
Pearce et al. [80]	Case-control	44	21 post-surgery Achilles tendon ruptures compared to 23 controls (ankle sprain)	X-ray		Laterally taken measurement of calcaneal pitch, lateral talocalcaneal, and tibiocalcaneal angles.	A significant difference exists between the tibiocalcaneal angle in patients with a confirmed rupture compared with a control group. X-ray can be used as an adjunct device. Could aid in plaster application.	15
Rominger at al. [58]	Prospective cohort	60	Post-surgery. 30 also MRI	Ultrasound + MRI	6–78 months	Ultrasound: 5–7.5 MHz during flexion/extension of foot. Medial-sagittal plane and 3 cm above calcaneus. Bilateral examination.	Tendon remained thicker postoperatively.	16
						MRI: T1/T2 MRI, sagittal, bilateral.	Ultrasound and MRI had a significant positive correlation with function, ultrasound however also correlated positively with physical disability and reduction in physical activity. Ultrasound preferred.	
Sarman et al. [75]	Retrospective cohort	16	Acute Achilles tendon rupture post operatively	Diffusor Tensor imaging (DTI) MRI	All at least 6 months post operatively. Median follow-up duration was 21 months (range 6–80 months)	3 T scanner T1/T2 images, bilateral examination. Axial, sagittal, and coronal T1-weighted. The microstructure of the AT was assessed by muscle fiber tracking and tendon continuity using the fractional anisotropy (FA) and Apparent Diffusion Coefficient (ADC) values by way of DTI.	DTI fractional anisotropy lower on injured side. Diffusion coefficient values correlated significantly with follow up time (r = 0.49–0.71). DTI can be used as an alternative noninvasive technique in the evaluation of tendon characteristics during the healing process.	15
Schepull et al. [83]	Prospective cohort	10	Achilles tendon ruptures surgically treated	RSA	6, 12, and 18 weeks and 1 year	During surgery, with a special injection needle, 2 tantalum beads with a diameter of 0.8 mm were placed in the distal part of the Achilles tendon and 2 beads were placed in the proximal stub.	RSA measures mechanical properties and combined with CT transverse area the elastic modulus can be measured. Functional results at 52 weeks correlated moderately	21

Table 3 (*Continued*)

Studies	Design	N	Pathology + Analysis	Imaging	Follow-Up	Imaging Characteristics	Outcomes and Conclusions	D&B Score
							with modulus (r = 0.76) at 6–18 weeks. RSA post-surgery can help aid treatment selection.	
Schepull et al. [82]	Reanalysis of data	65	Achilles tendon rupture, surgically treated. 61 at 7 weeks, 56 at 19 weeks, 53 at 52 weeks	CT (+RSA)	7. 19 and 52 weeks		Only a weak correlation between radiodensity and functional (r = 0.41) and subjective (r = 0.48) results at 1 year. No other associations. CT (+RSA) can quantify tissue healing through quantifying tissue density, allows assessment of re-rupture risk.	13
Schepull et al. [81]	Prospective randomized controlled trial	35	Achilles tendon rupture, surgical treatment, cast immobilization compared to tensional loading in randomized controlled trial	RSA + CT	7, 19 and 52 weeks		Correlation between elastic modulus and elongation at 7 weeks and the heel rise outcome at 52 weeks. No other significant correlations. Elastic modulus predicts tendon healing but may not matter in functional outcome.	25

Two studies provided diagnostic accuracy data on MRI. However, one study had an absence of false positives and true negatives [66] and one of true positives [69], making half of the calculations unobtainable. The sensitivity and specificity were calculated at 90.9% and 100% respectively. The LR+ of MRI was calculated at 0.91 and LR− at 1.0.

The methodological qualities of the studies varied greatly. Fig. 3 shows that the QUADAS-2 appraisal revealed a high risk of bias in the use of the reference standard. Additionally, the mean D&B score of the diagnostic accuracy studies proved the lowest at 15.6 (SD = 4.3). No other imaging modalities than ultrasound or MRI provided data on diagnostic accuracy.

Discussion

This study systematically reviewed the available literature on the role of imaging modalities in the diagnosis and monitoring of ATRs. Fifty-six studies were included, most concerning ultrasound (n = 37). The overall methodological quality as well as the number of cases of the included studies was low, warranting cautious interpretation of the results. No conclusions could be made on other imaging modalities than ultrasound and MRI as methodological quality varied (D&B SD = 5.8) and diagnostic and monitoring applicability remained unclear.

This review established the adjunct role of imaging in the diagnosis and monitoring of ATRs. Imaging can be used diagnostically to rule out an ATR and provide adjunct clinical information. During monitoring imaging provides healing-stage information that is unrelated to the clinical picture.

Ultrasound

The general ultrasound examination consisted of a 7.5 MHz probe analyzing a prone patient's injured and contralateral Achilles tendon. The probe frequencies seemed to increase moderately in more recent studies, showing the increased capabilities of ultrasonography in medical imaging.

The results supported and recommended ultrasound fulfilling a (adjunct) role in ATR diagnosis and monitoring. Ultrasound provides information on the type and level of rupture useful in the selection of treatment [29–32,36,41–46,48,50,52,56,57,63]. Additionally, ultrasound can determine healing process-related changes in the post-rupture Achilles tendon. However, these abnormalities showed little to no relevant relationship with treatment and the clinical picture [33,37,39,45,51,53,54,59,61]. As a monitoring device the value of ultrasound therefore remains limited to solely defining the healing process and tendon structure/mechanics; this warrants further research into how to personalize treatment based on this information. The addition of elastography to ultrasound can provide clinicians with even more healing and tendon mechanics information [34,35,61,64] possibly correlating with other outcomes [34,64], though more research is required, as only four studies using this technique were included.

MRI

The general MRI examination consisted of placing the patient supine in a 1.5 T machine with the ankle in the coil. Pathology was best seen on T2-weighted images [65,67,68,74,78]. A strong trend was seen for increased T strength in the MRI machines of more recent studies. Only six studies examined the diagnostic value of MRI [30,66,67,69,70,74], discouraging its use [66] or recommending ultrasound [30]. MRI was stated to be too time-consuming, costly, and inferior to ultrasound. MRI can visualize tendon structure and healing, but the relationship between MRI signal and the clinical picture proved inconclusive and limited [54,67,71–73,77]. More research is required into the correlation between MRI results and tendon function, as two studies did indeed find a significant positive correlation between MRI pathology and functional recovery [58,68]. Nevertheless, one of these studies determined ultrasound pathology positively correlated with both symptomatic and functional deficits, thereby proving more clinically valuable than MRI [58].

All studies comparing ultrasound to MRI and providing recommendations, recommended ultrasound for monitoring as

Table 4
Studies concerning diagnostic accuracy data.

Studies	Design	N	Pathology + Analysis	Imaging	Follow-Up	Outcome + Imaging Characteristics	Sensitivity	Specificity	LR+ LR−	D&B Score
Grechenig et al. [41]	Case-control	72	32 Acute traumatic ruptures, 40 chronic tendon complaints, 30 non-injured patients, intraoperative confirmation.	Ultrasound		Difference in MHz for Ultrasound (5–20), more MHz more clarity, compare to contralateral side. Higher frequencies best for analysis of tendon insertion.	100% (29/29) (95% CI = 86%–100%)	0% (0/3) (95% CI = 0%–69%)	LR+: 1.0 LR−: N/A	11
Griffin et al. [42]	Prospective case-control	22	24 with operatively confirmed Achilles tendon rupture, analysis of 22 ruptures, comparison of novice and expert analysis.	Realtime Achilles Ultrasound Thompson test (RAUT) and (static) Ultrasound (US)	<21 days after injury, on the day of surgery	13–6 MHz transducer. Patients were placed in the prone position, with the ankle hanging freely, bilateral examination. Analysis of 88 slides (bilateral: RAUT and static).	Expert RAUT:86.4% (95% CI = 79%–91.5%) Expert US: 79.6% (95% CI = 71.5%–85.9%)	Expert RAUT:91.7% (95% CI = 85.2%–95.6%) Expert US: 86.4% (95% CI = 79%–91.5%)	Expert RAUT: LR+:10.4 LR−: 0.15 Expert US: LR+:5.9 LR−:0.2	20
Hartgerink et al. [43]	Case-control	26	Partial vs. full thickness tears.	Ultrasound	Mean time between US and surgery 6.6 days for full and 216 days for partial thickness tears	7.5–12 MHz linear transducer, prone position, feet hanging over table. Longitudinal and transverse planes. Two false positive due to incomplete medial to lateral and superior to inferior scanning, can also be due to delay until surgery.	100% (14/14) (95% CI = 73%–100%)	83.3% (10/12) (95% CI = 51%–97%)	LR+: 7.0 LR−: 0.0	20
Margetic et al. [52]	Case-control and prospective cohort	100	Compare initial ultrasound with intraoperative (full vs. partial rupture). 88 operated, 12 treated conservatively.	Ultrasound	3, 5, 8, and 12 weeks	Linear 7.5 MHz probe. Longitudinal and transverse planes in a static and dynamic view. Patient prone, ankle neutral, both tendons scanned. Ultrasound signal correlated with clinical picture, healing process.	90.6% (78/88) (95% CI = 82%–96%)	100% (2/2) (95% CI = 20%–100%)	LR+: N/A LR−: 0.09	15
Paavola et al. [56]	Case-control	79	80 surgically treated tendons for varying complaints with preoperative ultrasound. 26 Achilles tendon ruptures confirmed. 11 partial ruptures.	Ultrasound	Duration between ultrasound and symptoms varied from hours to 7 years	Ultrasound, Linear 5–10 MHz, mainly 7.5 MHz transducer, patient prone with foot hanging over table, longitudinal and transverse images. Bilateral examination.	96% (25/26) (95% CI = 78%–99%)	100% (95% CI = 71%–100%)	LR+: N/A LR−: 0.04	16
Garras et al. [66]	Case-control	66	Preoperative MRI, surgical confirmation. 66 controls without MRI.	MRI	Average 5.1 days after injury	Two images "best" for tendon discontinuity, MRI time-consuming, costly, and less sensitive/specific than the Thompson Test.	90.9% (60/66) (95% CI = 81%–96%)	N/A	LR+: 0.91 LR−: N/A	18
Kuwada [69]	Case-control	28	Patients with Achilles tendon complaints. Preoperative MRI, surgical confirmation. Concerned 7 partial Achilles tendon ruptures.	MRI		MRI best for "large" tendon.	N/A	100% (7/7) (95% CI = 56%–100%)	LR+: N/A LR−: 1.0	9

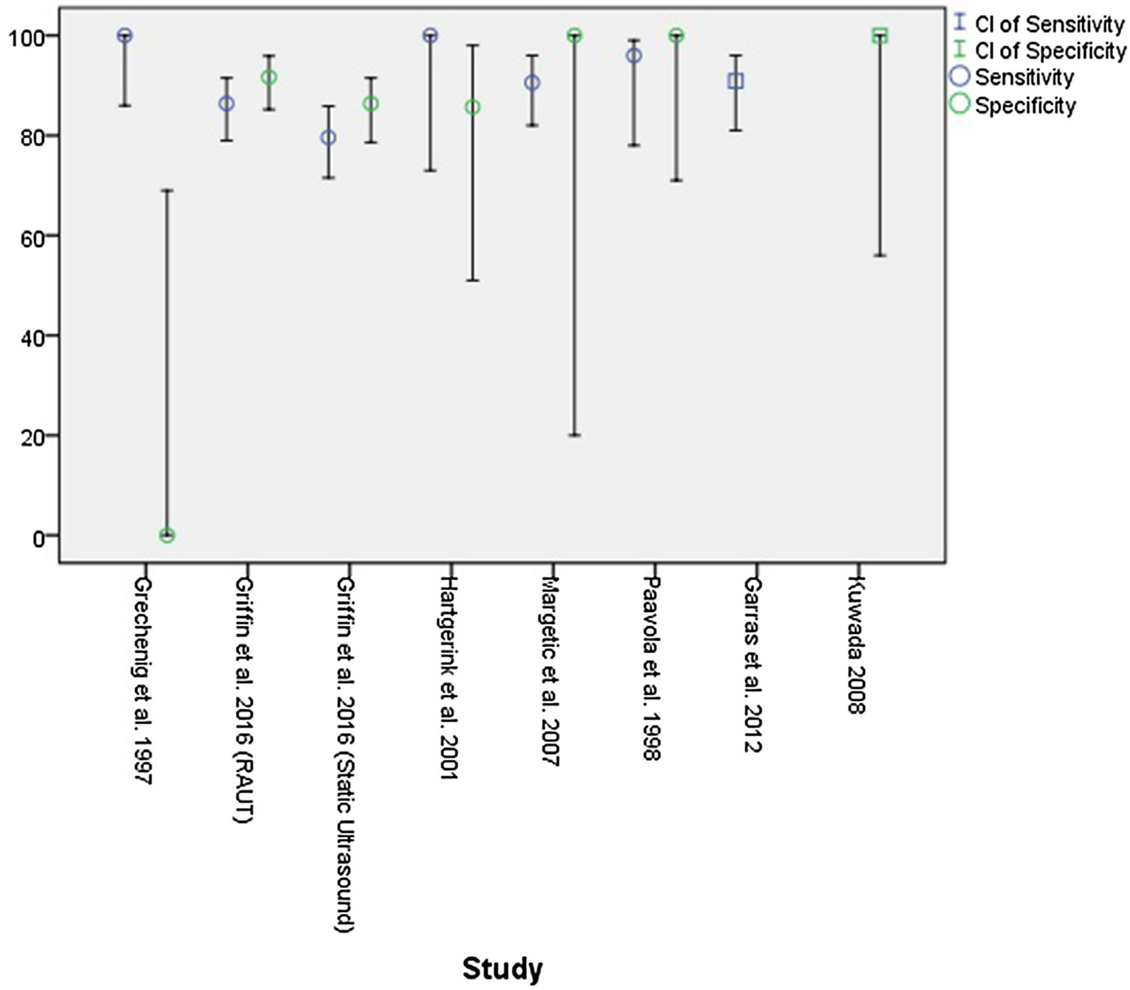

Fig. 2. Plot of sensitivity and specificity.

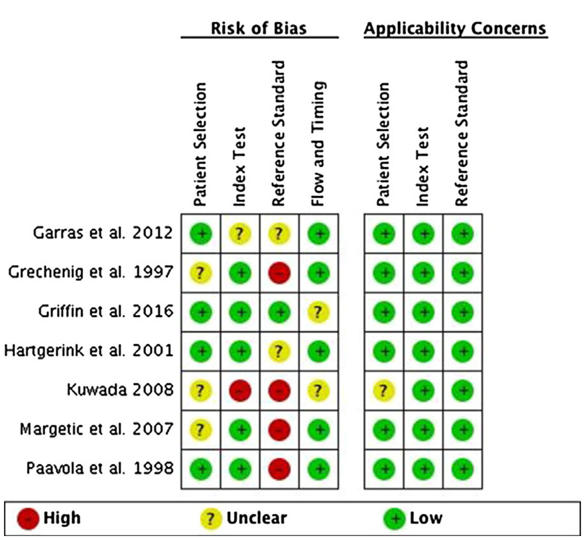

Fig. 3. QUADAS-2 scoring of risk of bias and applicability concerns.

well as diagnosis [30,54,58]. Ultrasound was stated to be cheaper, more dynamic, less time-consuming, correlated better with the clinical picture, and showed tendon defects in higher number [30,31,52,54,58,66,73]. Although Rominger et al. [58] found a positive correlation between MRI signal and functional recovery, they showed ultrasound to be more clinically relevant, as it correlated with both the patient's symptomatic and functional experience. Only Karjalainen et al. [49] explicitly recommended MRI as a monitoring modality.

Diagnostic accuracy

The diagnostic accuracy results show that both ultrasound and MRI can be applied to diagnose an ATR. However, drawing conclusions from these findings remains difficult: the diagnostic accuracy studies showed a high risk of bias and the lowest methodological quality, only five ultrasound and two MRI studies were included, some accuracy figures were unobtainable due to missing data, and there was a general lack of comparisons to other diagnostic tests.

The most methodologically-sound diagnostic accuracy study [42] showed ultrasound diagnosis is even more sensitive and specific when the Thompson test is applied during the examination. The LR- of ultrasound ranged from 0 to 0.23, confirming the role of ultrasound as a diagnostic adjunct in assessing the "difficult" patient, such as one with a plantaris tendon tear [30], by ruling out disease. Despite the promising sensitivity and specificity figures it should be noted that all studies applied intraoperative confirmation as the reference standard. Some (potential) controls however did not receive surgery; this could explain the large spread in specificity data. This case-control design has shown to overestimate diagnostic accuracy figures [84]. Additionally, due to the lack of data on diagnostic accuracy of other modalities and the high-risk of bias of included studies we believe more methodologically-sound research is warranted to establish the diagnostic accuracy of various imaging modalities.

Limitations and clinical implications

The publication restriction of including only studies published after 1995 may be seen as a limitation to this review. We decided not to include older studies as outdated imaging techniques are no longer applied in clinical practice and were hereby excluded from this review.

The results of this review encourage clinicians to perform a comprehensive clinical evaluation of ATR patients in the diagnostic and monitoring phases. Imaging can then be applied as an adjunct to rule out other injuries diagnostically or provide additional clinical information (type, level of rupture). As there seemed to be no association between abnormal findings on imaging and functional/subjective outcomes, it is recommended to interpret this (pathological) healing stage information as an adjunct and to rely primarily on the clinical picture during rehabilitative monitoring. This recommendation is in line with recent studies' conclusions on the value of imaging in other (sports) injuries such as hamstring injuries [85] ankle sprains [86] and fractures [87], groin injuries [88,89], and patellar tendinopathy [90].

Future directions

Due to the scarce and methodologically varied research into unconventional imaging modalities, the trend for higher frequency ultrasound probes and stronger Tesla MRI machines, and a growing medical and radiological field, more research is required into alternative ATR imaging methods. Perhaps there is still an undiscovered modality for diagnosis and treatment monitoring available. Ultrasound Tissue Characterisation (UTC), for example, introduced by van Schie et al. [91] has shown to be a novel monitoring technique correlating with subjective outcome in tendinopathy patients. This technique provides clinicians with information on tendon structure and quality and objectifies certain ultrasound parameters. Despite promising potential, this device has not yet been used in analyzing ATRs.

In conclusion, given the overall poor methodological quality of included studies, limited data on diagnostic accuracy as well as the ATR's clinical inconclusiveness, we recommend more high-quality research into ATR diagnostic and monitoring modalities.

Competing interests

The authors declare they have no competing interests.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.injury.2017.09.013.

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