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Early Predictors of Recovery From Nonoperatively Treated Achilles Tendon Rupture: 1 Year Follow-Up Study

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Keywords: Achilles tendon resting angle | shear wave elastography | strength deficit | tendon nonuniformity | ultrasonography

ABSTRACT

Purpose: To investigate early structural and mechanical predictors of plantarflexor muscle strength and the magnitude of Achilles tendon (AT) nonuniform displacement at 6 and 12 months after AT rupture.

Methods: Thirty-five participants (28 males and 7 females; mean ± SD age 41.7 ± 11.1 years) were assessed for isometric plantarflexion maximal voluntary contraction (MVC) and AT nonuniformity at 6 and 12 months after rupture. Structural and mechanical AT and plantarflexor muscle properties were measured at 2 months. Limb asymmetry index (LSI) was calculated for all variables. Multiple linear regression was used with the 6 and 12 month MVC LSI and 12 month AT nonuniformity LSI as dependent variables and AT and plantarflexor muscle properties at 2 months as independent variables. The level of pre- and post-injury sports participation was inquired using Tegner score at 2 and 12 months (scale 0–10, 10 = best possible score). Subjective perception of recovery was assessed with Achilles tendon total rupture score (ATRS) at 12 months (scale 0–100, 100=best possible score).

Results: Achilles tendon resting angle (ATRA) symmetry at 2 months predicted MVC symmetry at 6 and 12 months after rupture ($\beta = 2.530$, 95% CI 1.041–4.018, adjusted $R^2 = 0.416$, $p = 0.002$; $\beta = 1.659$, 95% CI 0.330–2.988, adjusted $R^2 = 0.418$, $p = 0.016$, respectively). At 12 months, participants had recovered their pre-injury level of sports participation (Tegner 6 ± 2 points). The median (IQR) ATRS score was 92 (7) points at 12 months.

Conclusion: Greater asymmetry of ATRA in the early recovery phase may be a predictor of plantarflexor muscle strength deficits up to 1 year after rupture.

Trial Registration: This research is a part of "nonoperative treatment of Achilles tendon rupture in Central Finland: a prospective cohort study" that has been registered in ClinicalTrials.gov (NCT03704532)

1 | Introduction

Achilles tendon rupture (ATR) can lead to long-term functional limitations in the affected limb [1, 2]. Regardless of the initial treatment strategy of operative or nonoperative care, some individuals regain more symmetrical side-to-side function, while others remain with pronounced deficits [1]. In addition to patient age [3], literature suggests that ultrasound imaging of the Achilles tendon (AT) and plantarflexor muscle structural characteristics may have a relevant role in predicting functional outcome [4–6]. For instance, early measurement of AT cross-sectional area (CSA) [4–6] and ultrasound elastography-based tendon stiffness may be associated with functional performance [4, 7]. In addition to ultrasound imaging, a larger intraoperative Achilles tendon resting angle (ATRA) has been related with a more symmetrical heel-rise performance in operatively treated patients [8]. These observations indicate a potential to establish clinically applicable methods to identify individuals who may require increased support during rehabilitation to avoid greater functional deficits in the long-term.

As methods to assess tendon properties have advanced, recent studies have investigated the nonuniform displacement within the AT [9]. This nonuniformity results from differential forces exerted on the three subtendons of the triceps surae muscle: medial gastrocnemius (MG), lateral gastrocnemius, and soleus [10], and is considered a sign of a healthy tendon [9]. Nonuniform displacement of the AT is reported as the relative change in displacement between different tendon regions during force production or passive range of motion [11]. AT nonuniformity appears to decrease after rupture [12, 13]; however, Khair et al. [12] showed that some individuals might recover this tendon function 1 year after nonoperatively treated ATR. Because of the novelty of assessing AT nonuniformity, it has not been investigated in follow-up settings, and information on parameters that may be associated with the recovery of this tendon property is needed.

Since only small improvements in functional tasks have been observed 1 year after ATR [14], more research should be focused on recovery during the first year after injury. Therefore, our aim was to assess whether early symmetry of AT and triceps surae muscle properties at 2 months after rupture were associated with side-to-side symmetry in isometric plantarflexor maximal voluntary contraction (MVC) and AT nonuniformity at 6 and 12 months. We examined whether participant age [3], sex [3], early symmetry of MG muscle and AT architecture [2, 4–7], ATRA [8, 15–17], or AT shear wave velocity (SWV, $m \times s^{-1}$) [7] measured at 2 months post-injury would serve as potential predictors of MVC and AT nonuniformity. We hypothesized that younger age and better structural and mechanical symmetry at 2 months would be related to better symmetry of MVC and AT nonuniformity at 6 and 12 months.

2 | Materials and Methods

2.1 | Study Design and Overall Procedure

This study is a part of a clinical cohort study "nonoperative treatment of Achilles tendon rupture in Central Finland: a prospective cohort study" (trial registration: NCT03704532). Measurements were carried out at 2, 6, and 12 months after nonoperatively treated AT rupture (mean ± SD time intervals 2.1 ± 0.3, 6.6 ± 1.1, and 12.5 ± 0.9 months) in a prospective follow-up design. The study was approved by the Research Ethics Committee of the Central Finland Health Care District (2U/2018) and was conducted in accordance with the Declaration of Helsinki. Each participant signed an informed consent prior to participation. The rights of the participants were protected in all circumstances.

2.2 | Participants and Recruitment

Thirty-five (28 males and 7 females) participants (mean ± SD age 41.7 ± 11.1 years [range 20–65 years], height 176.5 ± 8.6 cm, body mass 85.3 ± 16.9 kg, body mass index (BMI) 27.3 ± 4.7 kg/m^2) diagnosed with a unilateral ATR were recruited between 2018 and 2022. Recruitment was carried out at the Hospital Nova of Central Finland at the time of diagnosis. Participants were diagnosed within 14 days of acute ATR, with at least two out of four positive tests based on the American Academy of Orthopaedic Surgeons guidelines [18]. All participants received nonoperative care and early mobilization [19] (Table 1). Inclusion criteria were a minimum age of 18 years, normal walking ability (>100 m unaided) before rupture, and medical permission to walk unaided before the first measurement. Participants with systemic diseases (e.g., diabetes mellitus and hypertension) were excluded due to the association between these conditions and tendon health [20]. Other exclusion criteria were a rerupture, avulsion fracture of the calcaneus, and a previous ATR. Participant height and body mass were measured, and BMI calculated. Previous follow-up studies using similar methods have reported sample sizes of 22–86 individuals [4–6], and we aimed to include similar numbers.

2.3 | Study Protocol

A goniometer was used to measure ATRA in prone position, with the knee at a 90° angle [21]. The resting length of the MG

TABLE 1 | Nonoperative care and early mobilization procedure after rupture.

Weeks 0–2	Full equinus ankle cast
Weeks 2–4	Functional walking cast with 20°equinus allowing active plantarflexion exercises
	Active plantar flexion exercises were instructed to be performed five times a day
	Patients were encouraged to proceed to full weightbearing by Week 4
Weeks 4–8	Custom made functional walking orthosis with 1 cm heel wedge
	Removal of the heel wedge from the orthosis at Week 6
>Week 8	Removal of orthosis
	Instruction to use heel wedge in a shoe for 4 weeks
	Progressive rehabilitation instructions from a physiotherapist

subtendon was measured in prone with the ankle relaxed over the edge of examination table. Ultrasound was used to mark the proximal head of the calcaneus and the distal MG muscle–tendon junction. The distance between the marks was measured using a measuring tape [22]. In the same prone position, AT thickness and MG muscle architecture were acquired. First, AT thickness was imaged longitudinally over the free tendon using a 36 mm linear transducer. Next, images were taken to determine MG fascicle length and pennation angle at 50% of the muscle length between the crease of the knee and distal muscle–tendon junction [23], using a 60 mm linear transducer. Finally, CSA of the MG was imaged with the extended field of view at 50% of muscle length with the knee flexed to 90°, using the 36 mm linear transducer. A guide strap was placed around the calf to ensure imaging from the defined location along the horizontal plane. All B-mode ultrasound imaging was performed using the Aloka Alpha-10 system (Aloka, Tokyo, Japan) for both limbs in random order. We have previously reported the reliability of imaging gastrocnemius muscle architecture in our laboratory [24].

Supersonic shear wave elastography (Aixplorer Supersonic Imagine, v. 12.3.1 Aix-en-Provence, France) was used to assess tendon SWV ($m \times s^{-1}$). The technique serves as a surrogate of passive tissue stiffness, and it has been described in detail previously [25]. During imaging, participants were lying prone with both feet fixed at 25° ankle plantarflexion. The proximal head of the calcaneus was identified using B-mode ultrasound and marked on the skin. The shear wave elastography map of the AT was recorded longitudinally using a 38 mm linear transducer (2–10 MHz, SL10-2), with the distal edge of the transducer aligned with the mark on the proximal calcaneus (elasticity range 0–16.3 $m \times s^{-1}$; image depth adjusted according to the tendon thickness). The region of interest was set as wide as possible to cover the entire AT. The transducer was held still for ~5 s during each acquisition. All measurements were performed with a custom musculoskeletal preset (penetration mode, smoothing Level 5, persistence off, opacity 100%). Probe orientation was determined when multiple tendon fascicles and both superficial and deep tendon border were visible. Pressure between the probe and skin was kept to a minimum. Intrarater reliability of elastography imaging was tested for one rater with test–retest measurements performed 15 min apart in healthy pilot participants ($n = 16$). Reliability was tested using the intraclass correlation coefficient ($ICC_{3,1}$), standard error of measurement (SEM), minimum detectable change (MDC), and the coefficient of variation (CV). Intrarater reliability of shear wave elastography imaging yielded an ICC of 0.867 (95% CI −0.063 to 0.991), SEM 0.6 $m \times s^{-1}$, MDC 1.7 $m \times s^{-1}$, and CV 4.8%.

Isometric plantarflexor muscle MVC was tested with participants seated in an ankle dynamometer (University of Jyväskylä) with the knee extended and the hip in 60° flexion. Using inelastic straps, the foot was fixed to the dynamometer footplate in a neutral ankle position (0°) and the knee was secured in extension. The axis of the dynamometer was aligned with the presumed center of rotation of the ankle. Torque data were recorded using Spike2 software (v. 6.17, Cambridge Electronic Design Limited, Cambridge, UK) and sampled at a frequency of 1 kHz using a 16-bit analogue-to-digital converter (Power 1401, Cambridge Electronic Design, Cambridge, UK) connected to a computer. For conditioning, participants performed submaximal isometric contractions for 2 min. Between each maximal effort, participants were given 2 min rest and a minimum of three trials were recorded to obtain the highest MVC.

Then, the 36 mm linear transducer (Aloka, Tokyo, Japan) was placed longitudinally on the distal AT to record the internal displacement of the AT. After familiarization, a video of B-mode images was recorded during an isometric ramp contraction up to a target torque of 30% of the MVC of the uninjured limb, at a sampling frequency of 50 Hz. The reliability of imaging AT internal displacement in our laboratory has been reported previously [26].

Tegner score [27] was used to inquire the level of sports participation before injury and at 12 months after rupture. One-item Tegner score is graded on a scale of 0–10, with 0 points representing full disability in sports participation. Subjective perception of recovery was inquired using Achilles tendon total rupture score (ATRS) [28] at 12 months postrupture. The ATRS is calculated from 0 to 100 points, with 100 points indicating no functional deficits.

2.4 | Data Processing

Structural data were processed using ImageJ (1.44b, National Institutes of Health). The average values from two images were used for statistical analysis. Tendon thickness was analyzed 2 cm above the proximal head of the calcaneus. MG fascicle length was determined between the superficial and deep aponeurosis, and MG pennation angle from the angle between the fascicle and deep aponeurosis.

Shear wave velocity was processed using a custom software (ElastoGUI open software https://bio.tools/elastogui, University of Nantes, France) developed for MATLAB (v. R2022b, The MathWorks, Inc., Natick, MA, USA). The area of analysis was adjusted to cover the largest possible area within the superficial and deep tendon borders, and each pixel of the elastogram was converted to SWV based on the recorded color scale. Mean ± SD values of the analyzed areas for uninjured and injured limb were 1.1 ± 0.2 and $2.4 \pm 0.8\ cm^2$, respectively. Acceptable saturation and void levels of <3% and <0.1% were used. Saturation was present in 24 analyzed SWV recordings (average saturation % for uninjured and injured limbs: 0.4% and 0.2%).

Differential proximo-distal displacements within the sagittal section of the AT were analyzed in MATLAB (v. R2021b, MathWorks Inc, Natick, MA, USA) using 2D speckle tracking [9] adapted by Khair et al. [12] from cine B-mode ultrasound images. The region of interest was manually positioned over the distal tendon to ensure that only tendinous tissue was included. Within the region of interest, a grid of six locations across the thickness of the tendon and 11 locations across the length of the tendon was generated. Tendon nonuniformity was quantified as the difference between the minimum and maximum peak displacements within the tracked locations and normalized to the mean displacement of the six locations across the tendon.

Limb asymmetry index (LSI) was calculated for all variables as percentage (%) difference between limbs: $\frac{\text{Injured} - \text{uninjured}}{\text{uninjured}} \times 100$.

2.5 | Statistical Analysis

Statistical analyses were performed using JASP (JASP v. 0.16.4, Amsterdam, Netherlands). Descriptive statistics are presented as means and standard deviations (SD) as well as medians and interquartile ranges (IQR). Statistical significance was defined as $p < 0.05$. Skewness and kurtosis were checked to ensure data normality. Three forward multiple linear regression models were constructed using MVC LSI at 6 and 12 months and normalized AT nonuniformity at 12 months as dependent variables. To determine eligible independent variables to the multiple regression models, simple linear regressions between the main outcomes and potential independent variables were computed for both 6 and 12 month time points. Independent variables were considered eligible with a significance level of <0.05. Because of the small sample size, a maximum of two independent variables with the highest β values were included in the multiple regression models. Age and sex were retained in the models as clinically important variables. The basic assumptions of the regression models were carefully confirmed according to appropriate test diagnostics. All correlations between the independent variables were <0.7 to ensure the absence of multicollinearity.

3 | Results

3.1 | Cohort Characteristics

Thirty-five participants were included. Four participants were unable to attend the assessments at 6 months due to personal schedules. Therefore, 31 individuals were included in the analysis for 6 month time point and 35 individuals for 12 months. The average pre-injury and 12 month Tegner scores were 6 ± 2 and 6 ± 2, respectively. The median (IQR) ATRS score was 92 (17) points at 12 months. Descriptive statistics of the measured outcomes are summarized in Tables 2 and 3. Further information on side-to-side differences between limbs and differences between sexes can be found in (Appendices S1–S4).

3.2 | Simple Linear Regression

Results for simple linear regressions are presented in Table 4. Based on these associations, ATRA LSI and MG fascicle length LSI were selected as independent variables for the multiple regression model predicting 6 month MVC symmetry, and ATRA LSI and MG subtendon length LSI for the model predicting 12 month MVC symmetry. The 6 month multiple regression was not done for AT nonuniformity, as none of the potential predictors were significant. ATRA LSI was used in the model predicting the symmetry of AT nonuniformity at 12 months.

3.3 | Multiple Linear Regression

Regression models for MVC symmetry at 6 and 12 months explained 41.6% and 41.8% of the variance, respectively (Table 5). In both models, ATRA symmetry at 2 month time point emerged as a single significant predictor of MVC symmetry (Figure 1).

4 | Discussion

The results showed that greater symmetry of ATRA at 2 months was associated with greater plantarflexor muscle strength symmetry at 6 and 12 months after rupture. These findings complement prior work [4–6, 8] identifying clinical variables that predict later functional outcomes. We did not find associations between the measured variables and AT nonuniformity, and further research is warranted to investigate the relationship between tendon function and the morphomechanical properties of the triceps surae muscle–tendon unit. Identification of factors affecting AT nonuniformity after rupture may require investigation at individual or cluster level [12].

4.1 | Symmetry of Maximal Voluntary Contraction

Based on the multiple regression models, a 1% improvement in ATRA LSI would result in a 2.5% improvement in MVC LSI at 6 months and a 1.6% improvement at 12 months. These findings align with previous cross-sectional studies reporting a

TABLE 2 | Descriptive statistics of potential predictor variables measured at 2 months.

	Uninjured limb	Injured limb	% difference (LSI)
MG CSA (cm^2)	15.17 ± 4.27	12.54 ± 3.11	−15.8
MG fascicle length (cm)	4.88 ± 0.77	4.42 ± 0.59	−8.1
MG pennation angle (°)	25.49 ± 3.40	25.07 ± 5.82	−1.1
MG subtendon length (cm)	18.15 ± 2.01	19.72 ± 2.20	8.8
AT thickness (cm)	0.47 ± 0.08	0.96 ± 0.19	109.4
ATRA	131.87 ± 6.31	122.84 ± 6.10	−6.8
AT SWV ($m \times s^{-1}$)	10.19 ± 1.85	6.37 ± 1.80	38.2

Note: All values are presented as means ± SD.
Abbreviations: ATRA = Achilles tendon resting angle, AT = Achilles tendon, CSA = cross-sectional area, LSI = limb asymmetry index, SWV = shear wave velocity.

TABLE 3 | Descriptive statistics of the main outcomes measured at 6 and 12 months.

	6 months			12 months		
	Uninjured limb	**Injured limb**	**% difference (LSI)**	**Uninjured limb**	**Injured limb**	**% difference (LSI)**
MVC (Nm)	228.31 ± 64.34	151.78 ± 66.61	−33.8	242.47 ± 71.68	184.95 ± 70.91	−23.7
AT nonuniformity (mm)	2.16 ± 1.11	0.88 ± 0.68	−53.2	2.32 ± 1.19	1.10 ± 0.71	−43.0
Normalized AT nonuniformity	0.52 ± 0.24	0.22 ± 0.17	−39.3	0.65 ± 0.30	0.26 ± 0.17	−56.3

Note: All values are presented as means ± SD.
Abbreviations: AT = Achilles tendon, LSI = limb asymmetry index, MVC = maximum voluntary contraction.

correlation between ATRA and heel-rise performance after ATR [15–17]. Furthermore, Carmont and colleagues [8] found an association between greater intraoperative ATRA and 12 month heel-rise performance in operatively treated patients, supporting our findings. The results of this study show that in addition to heel-rise performance, ATRA is also related to the isometric plantarflexor muscle strength deficit tested with ankle in neutral position, suggesting that ATRA is associated with plantarflexor force production capacity under different conditions. It is possible that the force production capacity of the injured limb could differ if tested at a different ankle angle due to the elongated tendon [29]. It is reasonable to assume that the current sample would show smaller plantar flexion strength impairment in a more dorsiflexed ankle position. Given that the ankle resting position can be directly altered by the increased tendon length after rupture, and that tendon elongation is responsible for the altered configuration in the muscle–tendon unit [30], early measurement of ATRA could serve as a potential clinical tool for screening patients at risk for worse functional outcomes. As ATRA is easily applicable in clinical practice and research, future studies should investigate whether cutoff values of interlimb symmetry could be established to identify risk of inferior functional outcomes.

Shear wave-based stiffness of the AT has been observed to acutely decrease after rupture and gradually increase in accordance with tendon healing [7, 31]. Although AT SWV did not enter our prediction models, simple linear regressions showed a moderate positive association between AT SWV and both 6 and 12 month MVC LSI. Interestingly, similar observations have been obtained in earlier studies using ultrasound elastography methods [4, 7]; for instance, early measurement of AT dynamic shear modulus [4] has been associated with objectively measured patient function at 6 months after ATR. These findings suggest that early recovery of stiffness in the injured tendon might reflect a favorable recovery of biomechanical properties that are essential for regaining tendon resilience for later loading and functional performance.

Although the participants had asymmetry in plantarflexor muscle strength throughout the follow-up period, on average they were able to return to pre-injury levels of sports participation 1 year after rupture. The average Tegner activity score both before and after injury was Level 6, which corresponds to participation in recreational sports at least five times a week [27]. Previous studies have reported significantly reduced levels of physical activity 1 and 2 years after rupture [8, 14]. Patient-reported scores do not appear to address the deficits in muscle–tendon unit structure or objective functional outcomes in general population [1], although they are an important measure of the subjective perception of recovery.

4.2 | Symmetry of Achilles Tendon Nonuniformity

The general understanding of factors associated with nonuniform AT subtendon displacement is yet limited [11, 32]. In the present study, we hypothesized that asymmetry of AT nonuniform displacement could be predicted by early resting measures of AT and triceps surae muscle properties. Since nonuniform displacement results from differential forces

TABLE 4 | Results for simple linear regressions between outcome variables and potential predictors.

	R^2	β	95% CI	p
Dependent variable: 6 month MVC LSI				
Age	0.092	−0.500	−1.095–0.096	0.097
BMI	0.037	−0.699	−2.052–0.653	0.299
MG CSA (cm^2)	0.011	0.133	−0.355–0.620	0.582
MG fascicle length (cm)	0.138	0.495	0.016–0.974	0.043
MG pennation angle (°)	0.126	−0.284	−0.574–0.006	0.054
MG subtendon length (cm)	0.076	−0.831	−1.975–0.314	0.148
AT thickness (cm)	0.002	−0.016	−0.147–0.115	0.803
ATRA	0.455	2.763	1.615–3.910	<0.001
AT SWV ($m \times s^{-1}$)	0.262	0.473	0.091–0.854	0.018
Dependent variable: 12 month MVC LSI				
Age	0.188	−0.654	−1.135 to −0.172	0.009
BMI	0.011	−0.372	−1.627–0.883	0.551
MG CSA (cm^2)	0.001	0.033	−0.423–0.488	0.885
MG fascicle length (cm)	0.245	0.631	0.232–1.029	0.003
MG pennation angle (°)	0.086	−0.229	−0.497–0.039	0.092
MG subtendon length (cm)	0.137	−1.105	−2.121 to −0.090	0.034
AT thickness (cm)	0.000	5.514×10^{-4}	−0.120–0.121	0.993
ATRA	0.218	1.871	0.615–3.126	0.005
AT SWV ($m \times s^{-1}$)	0.221	0.429	0.064–0.794	0.023
Dependent variable: 6 month normalized AT nonuniformity LSI				
Age	0.031	1.142	−1.420–3.705	0.368
BMI	0.024	−2.067	−7.374–3.240	0.431
MG CSA (cm^2)	0.032	−1.004	−3.288–1.280	0.374
MG fascicle length (cm)	0.113	1.755	−0.273–3.784	0.087
MG pennation angle (°)	0.128	−1.063	−2.208–0.082	0.067
MG subtendon length (cm)	0.004	−0.786	−5.638–4.065	0.741
AT thickness (cm)	0.001	−0.037	−0.578–0.504	0.890
ATRA	0.124	−5.993	−12.425–0.439	0.067
AT SWV ($m \times s^{-1}$)	0.189	−1.483	−3.005–0.040	0.056
Dependent variable: 12 month normalized AT nonuniformity LSI				
Age	0.113	0.920	−0.007–1.846	0.052
BMI	0.057	1.583	−0.737–3.903	0.174
MG CSA (cm^2)	0.001	−0.056	−0.895–0.783	0.893
MG fascicle length (cm)	0.001	0.055	−0.802–0.912	0.896
MG pennation angle (°)	0.030	0.244	−0.264–0.753	0.335
MG subtendon length (cm)	0.036	1.032	−0.959–3.023	0.298
AT thickness (cm)	0.060	0.152	−0.069–0.374	0.171
ATRA	0.140	−2.713	−5.134 to −0.291	0.029
AT SWV ($m \times s^{-1}$)	0.125	−0.654	−1.439–0.131	0.098

Note: All variables were analyzed as limb asymmetry index values (percentage difference between limbs).
Abbreviations: ATRA = Achilles tendon resting angle, AT = Achilles tendon, BMI = body mass index, CSA = cross-sectional area, MG = medial gastrocnemius, MVC = maximum voluntary contraction, SWV = shear wave velocity.

TABLE 5 | Results for multiple linear regression models predicting MVC and AT nonuniformity symmetry at 6 and 12 months after rupture.

Model with included predictors	β	95% CI	p
MVC LSI (%) at 6 months, $n=30$			
Adjusted $R^2=0.416$, F (4, 25) = 6.171, RMSE = 13.72			
ATRA LSI (%) at 2 months	2.530	1.041–4.018	0.002
MG fascicle length LSI (%) at 2 months	0.217	−0.213–0.647	0.309
MVC LSI (%) at 12 months, $n=33$			
Adjusted $R^2=0.418$, F (4, 28) = 5.027, RMSE = 14.08			
ATRA LSI (%) at 2 months	1.659	0.330–2.988	0.016
MG subtendon length LSI (%) at 2 months	−0.693	−1.647–0.262	0.148
Normalized AT nonuniformity LSI (%) at 12 months, $n=34$			
Adjusted $R^2=0.123$, F (3, 30) = 2.548, RMSE = 28.83			
ATRA LSI (%) at 2 months	−2.243	−4.751 to −0.266	0.078

Abbreviations: ATRA = Achilles tendon resting angle, AT = Achilles tendon, LSI = limb asymmetry index, MG = medial gastrocnemius, MVC = maximal voluntary contraction, SWV = shear wave velocity.

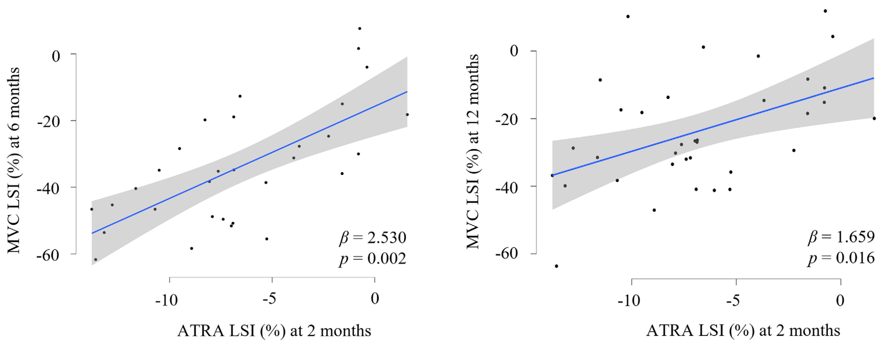

FIGURE 1 | Relationship between Achilles tendon resting angle symmetry at 2 months and isometric plantarflexor muscle maximal voluntary contraction symmetry at 6 and 12 months. ATRA = Achilles tendon resting angle, LSI = limb asymmetry index, MVC = maximal voluntary contraction.

applied to each subtendon [33], changes that occur to the fascicle length of the triceps surae muscles, in addition to interfascicular matrix adhesions after rupture may explain the reduction in AT nonuniformity [34]. The relationship between the architecture of a given muscle and its excursion capacity is well established [35]. Contrary to expectations, the multiple regression model was insignificant, although the initial simple regression showed an inverse association between the early measurement of ATRA and AT nonuniformity at 12 months. This association would suggest that a greater difference in ATRA between limbs would be related to a smaller asymmetry in AT nonuniformity. This inverse relationship appears to be controversial, and there may be confounding factors affecting the observation.

The AT has a complex twisted geometry [36], which creates a challenge for in vivo assessment during functional tasks [32]. As the mechanical behavior of the AT is composed of three subtendons, we may have to account for the entire triceps surae to better understand the internal tendon behavior. Triceps surae muscles have heterogenous muscle fiber characteristics [37] and activation during locomotion [38], whereas the three subtendons show differential mechanical properties [32, 39]. Cadaveric studies [36] have shown that the magnitude of AT twisting varies in healthy individuals. Depending on the degree of rotation of each subtendon from proximal to distal orientation, three groups of twisting patterns have been distinguished across the population [36]. It is possible that averaging the nonuniformity values from a sample of individuals with varying degrees of twisting may mask details of nonuniform displacement of the AT. Therefore, stratifying the data at the cluster level could provide further insight into the factors influencing AT nonuniformity after rupture.

4.3 | Limitations

This study comes with some limitations. First, the age range of the participants was wide, which may have resulted in different baseline characteristics of the muscle–tendon unit and healing progression between participants. Second, detailed individual progress with rehabilitation exercises or additional visits to physiotherapy after the initial nonoperative treatment was not controlled for, which may have led to differences in rehabilitation procedures. However, in terms of age and potential differences in rehabilitation, they are representative of the general population of patients with ATR [40]. Third, the pre-injury Tegner score was inquired retrospectively at 2 months after injury, which may introduce a possibility of recall bias. Finally, the small sample size limits generalizability of the present findings.

4.4 | Perspective

ATRA measured at 2 months was found to be associated with plantarflexor strength deficit within 1 year after rupture, which aligns with previous studies reporting a relationship between ATRA and heel-rise performance [8, 15–17]. The findings suggest that ATRA may be a relevant biomarker of the progression of tendon healing and have potential as a clinical tool for identifying patients at risk of prolonged strength deficits.

Author Contributions

T.F., **J.P.**, and **N.C.** conceived and designed the study. **T.F.** obtained funding for the study. **T.F.**, **R.M.K.**, **M.S.**, **A.R.**, and **V.P.** contributed to the data collection. **M.S.** was responsible for data analysis, statistical analysis, and drafting the manuscript. **T.F.** and **A.J.H.** were responsible for supervision. All authors contributed to the writing of the final manuscript and critically revised the report for important intellectual content. All authors approved the final manuscript.

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Ethics Statement

Ethics approval was granted by the Research Ethics Committee of the Central Finland Health Care District (2U/2018).

Consent

The authors affirmed that study participants provided informed consent prior their participation in this research.

Conflicts of Interest

The authors declare no conflicts of interests.

Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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