Author(s): Khair, Ra'ad M.; Stenroth, Lauri; Péter, Annamária; Cronin, Neil J.; Reito, Aleksi; Paloneva, Juha; Finni, Taija

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ORIGINAL ARTICLE

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Non-uniform displacement within ruptured Achilles tendon during isometric contraction

Ra'ad M. Khair[1] | Lauri Stenroth[2] | Annamária Péter[1] | Neil J. Cronin[1,3] | Aleksi Reito[4] | Juha Paloneva[4] | Taija Finni[1]

[1]Faculty of Sport and Health Sciences, Neuromuscular Research Center, University of Jyväskylä, Jyväskylä, Finland

[2]Department of Applied Physics, University of Eastern Finland, Kuopio, Finland

[3]Department for Health, University of Bath, Bath, UK

[4]Central Finland Health Care District, Jyväskylä, Finland

Correspondence
Ra'ad M. Khair, Neuromuscular Research Center, Faculty of Sport and Health Sciences, University of Jyväskylä, PO Box 35, Jyväskylä FI-40014, Finland.
Email: raad.m.khair@jyu.fi

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The purpose of this study was investigate tendon displacement patterns in non-surgically treated patients 14 months after acute Achilles tendon rupture (ATR) and to classify patients into groups based on their Achilles tendon (AT) displacement patterns. Twenty patients were tested. Sagittal images of AT were acquired using B-mode ultrasonography during ramp contractions at a torque level corresponding to 30% of the maximal isometric plantarflexion torque of the uninjured limb. A speckle tracking algorithm was used to track proximal-distal movement of the tendon tissue at 6 antero-posterior locations. Two-way repeated measures ANOVA for peak tendon displacement was performed. K-means clustering was used to classify patients according to AT displacement patterns. The difference in peak relative displacement across locations was larger in the uninjured (1.29 ± 0.87 mm) than the injured limb (0.69 ± 0.68 mm), with a mean difference (95% CI) of 0.60 mm (0.14-1.05 mm, $P < .001$) between limbs. For the uninjured limb, cluster analysis formed 3 groups, while 2 groups were formed for the injured limb. The three distinct patterns of AT displacement during isometric plantarflexion in the uninjured limb may arise from subject-specific anatomical variations of AT sub-tendons, while the two patterns in the injured limb may reflect differential recovery after ATR with non-surgical treatment. Subject-specific tendon characteristics are a vital determinant of stress distribution across the tendon. Changes in stress distribution may lead to variation in the location and magnitude of peak displacement within the free AT. Quantifying internal tendon displacement patterns after ATR provides new insights into AT recovery.

KEYWORDS
Achilles tendon, clustering, non-surgical treatment, rupture, ultrasound speckle tracking

1 | INTRODUCTION

Achilles tendon rupture (ATR) is a disabling condition with a growing yearly incidence of 20-35 per 10 000 individuals.[1,2] Regardless of the treatment option, ATR leads to long-term deficits in anatomy, function and physical activity that persist several years post-ATR.[3] The factors leading to better ATR recovery are still poorly understood. Thus, although the area is frequently studied, the optimal treatment option is still debatable. Treatment is either surgical or non-surgical, and these modes involve different immobilization periods.[4-6] Early mobilization seems to lead to better functional outcomes, a higher quality of life and a shorter rehabilitation period.[7-10]

The Achilles tendon (AT) is a composite of the three sub-tendons arising from the triceps surae (TS) muscles: medial gastrocnemius, lateral gastrocnemius, and soleus. The tendon fibers twist so that at the point of insertion, lateral gastrocnemius fibers end up on the ventral side, medial gastrocnemius fibers become dorsal, and soleus fibers become medial. The twisting of the sub-tendons varies among individuals and can be classified into three types depending on the degree of torsion.[11]

The twisting of the subtendons is thought to cause heterogeneity of strain within the tendon. Relative displacement within Achilles tendon has been shown to occur between subtendons[12] and between adjacent tendon fascicles.[13] The fascicles originating from different TS muscles exert differential forces and strains on each sub-tendon[12,14] and are likely to cause non-uniformities between fascicles arising from different muscle heads.[12,14] In several studies, the anterior (deep) tendon has been reported to displace more than the posterior (superficial) tendon.[15-18] Furthermore, the different degrees of torsion among the population would lead to distinct non-uniform displacement patterns within the AT for each group.

The ability of the tendon fascicles and sub-tendons to slide relative to each other is considered a sign of healthy tendon,[16,19] and it is usually overlooked in the management of ATR. Recently, it has been suggested that during muscle contraction, non-uniform displacement within the AT is an indication of healthy AT function,[16] whereas surgically treated injured AT has been found to display more uniform within-tendon displacements 1 year post-ATR.[16,20] In studies to date, participant data have been presented as mean values, but due to individual anatomical variation,[11] it may be expected that AT displacement patterns are also individual-specific.

The aim of the present study was to investigate tendon displacement patterns in non-surgically treated patients 14-months after acute ATR, and to classify patients into groups based on their AT displacement patterns. After identifying groups, the aim was to explore whether individuals in the different groups showed differences in factors previously associated with good recovery from ATR, such as plantarflexion strength, displacement pattern, and preferred gait speed.[16,20,21] We hypothesized that ruptured AT would show a more uniform displacement pattern compared to the contralateral AT and expected different displacement behaviors in different cluster groups.

2 | METHODS

The study is part of a clinical cohort study "Non-operative treatment of Achilles tendon Rupture in Central Finland: a prospective cohort study – NoARC" (trial registration: NCT03704532). The Ethics Committee of the Central Finland Health Care District approved the study (2U/2018).

2.1 | Non-surgical treatment protocol

All participants were treated non-surgically in combination with early mobilization. Immediately after ATR, the ankle was cast in full equinus for two weeks. After two weeks, the foot was allowed to move into plantarflexion using a 20° equinus open sole cast. A custom-made functional walking orthosis with 1 cm thick heel wedge was delivered to the patients at week 4, and patients were encouraged to bear full weight. At 8 weeks, the orthosis was removed, and progressive physiotherapy began. The patients were instructed to use a heel wedge for 4 weeks after returning to daily activities.[22]

2.2 | Participants

Twenty patients (17 males, 3 females) within the Central Finland Health Care District agreed to participate (mean $\pm$ SD age: 43.7 $\pm$ 9.1 years, height: 1.75 $\pm$ 0.08 m, body mass: 81.91 $\pm$ 12.68 kg). Acute rupture occurring <14 days before was diagnosed using guidelines by the American Academy of Orthopedic Surgeons. Inclusion criteria were a minimum of 2 of the following 4 criteria: a positive Thompson test, decreased plantarflexion strength, presence of a palpable gap, and increased passive ankle dorsiflexion with gentle manipulation.[23] Other inclusion criteria included clear onset of symptoms, closed rupture, residence in the catchment area of the hospital district, minimum age of 18, ability to understand and speak Finnish, and normal walking ability (>100 m unassisted before rupture). The exclusion criterion included an avulsion fracture of the calcaneus or a re-rupture. Two participants with a re-occurring rupture were admitted for surgical treatment and excluded from the sample. Participants signed an informed consent explaining the details of the study, possible risks, and gave permission to use data for research purposes. Participants were tested 14.1 $\pm$ 1.7 months post-ATR.

2.3 | Protocol

Upon arrival to the laboratory, participants sat in a custom-made ankle dynamometer (University of Jyväskylä, Finland) with ankle at 90°, hip at 120° of flexion and the knee fully extended. A 3.6-cm linear ultrasound probe (UST-5411, Aloka alpha10, Japan) was attached over the distal AT (Figure 1). After performing a series of submaximal contractions as a warm-up, data collection started with the uninjured leg. Maximal voluntary isometric contractions (MVCs) were followed by unilateral contractions corresponding to the absolute torque level of 30% MVC of the uninjured limb. Participants were then asked to walk at their preferred speed across a 10-meter walkway, with the instruction "walk at the speed you normally walk when walking freely." Walking speed as an

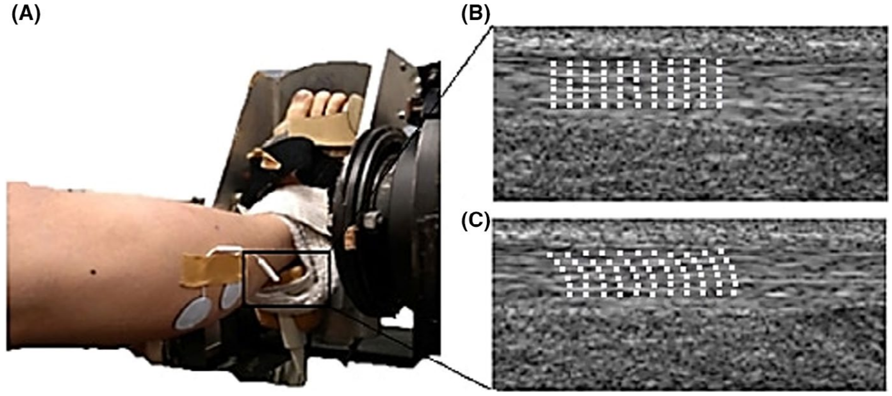

FIGURE 1 An overview of the torque measurement setup (A) and an example of ultrasound image analysis (B, C). The probe was fixed with an elastic bandage over the distal AT. B: The tendon at rest with the grid of 66 nodes generated across the AT (11 across the length and 6 across the width) overlaid on the image. C: The same grid of nodes during 30% MVC ramp contraction

average of 3 trials was determined using photocells placed at the beginning and end of the walkway.

2.4 | Data collection and analysis

For MVCs, the rotation axis of the ankle joint was carefully aligned with the rotation axis of the dynamometer (equipped with Precision TB5-C1, Raute, Nastola, Finland load cell). Torque was sampled with a 16-bit AD-board (Power 1401, CED Limited, Cambridge, England) at a sampling frequency of 1KHz. Following 3-5 familiarization trials, subjects performed 2-3 maximal 3-second plantarflexions with 1 minutes recovery between trials. Cine B-mode ultrasound images were then taken distally from the AT during an isometric ramp contraction up to 30% of the uninjured limb's MVC, at a sampling frequency of 50 Hz and operating frequency of 10 MHz.

Recently, ultrasonic speckle tracking has been validated to allow quantification of AT internal movement.[15,16] In this study, the approach of Slane and Thelen was followed.[16] The speckle tracking algorithm was implemented in MATLAB (R2018a, MathWorks Inc, Natick, MA, USA). The region of interest (ROI) was manually positioned over the distal part of the tendon. The size of the ROI was adjusted individually to ensure that only the tendon tissue was included. Inside the ROI, a grid of six locations across the thickness of the tendon and eleven across the length of the tendon was generated (Figure 1B). All tracking was visually monitored to ensure that the ROI remained within the tendon throughout the movement. Displacements of nodes along each of the six antero-posterior rows were averaged and peak displacements of the average data were extracted for analysis. The 6 locations across the tendon are referred to starting from superficial (location 1), to deep (location 6) respectively. The reliability of tracking was evaluated by analyzing the same video twice. This revealed 0.2% change in mean with a correlation of rp = 0.94, $P < .01$. The values and locations of maximal and minimal displacement across the tendon were extracted. Tendon peak relative displacement was calculated for both limbs (uninjured/injured) as the difference between minimal and maximal displacement in the tendon.

2.5 | Statistical analysis

All statistical analyses (except clustering) were performed using SPSS (IBM SPSS Statistics for Windows, Release 24.0, Chicago, Illinois). The level of significance was set at $P < .05$.

Two-way repeated measures ANOVA was performed for peak tendon displacement (6 locations) and limb condition (uninjured/injured). When the assumption of sphericity determined by Mauchly's test was violated, Greenhouse-Geisser adjustment was applied. Bonferroni-adjusted post hoc test was used to compare displacement values between locations for each group separately.

Two-sided paired *t* tests were used to compare MVC torque values between limbs, and to compare maximal and minimal displacement values at the limb and cluster level. Non-parametric Wilcoxon signed rank test and two-sided paired t tests were used to compare peak relative displacement between limbs due to the skewness of the data. Multiple linear regression analysis was used to examine the relationship between MVC and peak relative displacement while controlling for patient age. Preferred walking speed, submaximal contraction (MVC30%), tendon peak relative displacement, locations of maximum and minimum displacement between uninjured clustered groups, and MVC torque were compared between cluster groups for each limb separately using Independent Samples t test for the injured limb and one-way ANOVA for the uninjured limb. Descriptive data are presented as mean ± standard deviation.

K-means clustering (R clustering package/JASP version 0.11.1, Amsterdam, Netherlands) was used to classify patients according to AT displacement patterns. Cluster numbers (ie, the value of K) were chosen using the elbow method with respect to the Bayesian information criterion (BIC)

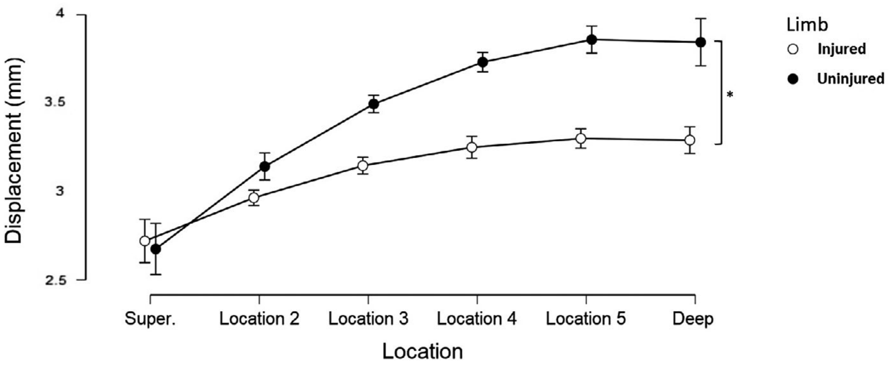

FIGURE 2 Peak displacement (mm) in each of the six locations across the tendon width while performing 30% MVC, starting with superficial and moving deeper in order. *Significant difference between groups (P = .032)

TABLE 1 Bonferroni-adjusted post hoc comparisons showing corrected mean differences (95% CI) in peak displacement (mm) between 6 locations across the Achilles tendon

Uninjured Limb	Super.	Location 2	Location 3	Location 4	Location 5	Deep
Superficial	—	0.44 (0.18-0.69)*	0.77 (0.33-1.20)*	0.99 (0.43-1.54)*	1.11 (0.48-1.73)*	1.09 (0.09-1.82)*
Location 2	—	—	0.33 (0.14-0.52)*	0.55 (0.23-0.87)*	0.67 (0.24-1.10)*	0.66 (0.06-1.25)*
Location 3	—	—	—	0.22 (0.07-0.37)*	0.34 (0.05-0.63)*	0.33 (0.17-0.82)
Location 4	—	—	—	—	0.12 (0.05-0.29)	0.11 (0.28-0.49)
Location 5	—	—	—	—	—	0.01 (0.21-0.24)
Injured Limb						
Superficial	—	0.23 (0.05-0.51)	0.40 (0.05-0.84)	0.50 (0.02-1.01)	0.54 (0.04-1.04)*	0.53 (0.09-0.98)*
Location 2	—	—	0.17 (0.03-0.34)	0.27 (0.01-0.52)*	0.31 (0.04-0.59)*	0.30 (0.02-0.63)
Location 3	—	—	—	0.10 (0.01-0.19)*	0.14 (0.02-0.31)	0.13 (0.19-0.46)
Location 4	—	—	—	—	0.05 (0.06-0.16)	0.04 (0.26-0.34)
Location 5	—	—	—	—	—	0.08 (0.20-0.19)

* Significant difference between locations (P < .05).

value. Clustering was repeated 5 times for each group and confirmed that each data point was consistently assigned to the same cluster group. Furthermore, to explore the validity of clustering, two-way repeated measures ANOVA for peak tendon displacement (6 locations) and clustered groups as a factor was performed for the injured and uninjured limbs separately.

3 | RESULTS

Torque at 100% MVC was significantly lower in the injured limb (mean ± SD: 136.25 ± 42.49 Nm) compared to the uninjured limb (178.47 ± 39.92 Nm), with a mean difference (95% CI) of 42.2 Nm (26.09-58.37 Nm, P < .001). During submaximal contractions, the same torque level was reached: 53.19 ± 11.84 Nm for the uninjured limb and 53.22 ± 12.38 Nm for the injured limb, with a mean difference (95% CI) of 0.04 Nm (−2.26-2.33 Nm, P = .97). There were significant differences between maximum and minimum displacement for both limbs, with mean differences (95% CI) of 1.29 mm (0.88-1.7 mm, P < .001) and 0.69 mm (0.37-1.00 mm, P < .001) in the uninjured and injured limbs, respectively. Peak relative displacement was significantly larger in the uninjured (mean ± SD: 1.29 ± 0.87 mm) than the injured limb (0.69 ± 0.68 mm) according to the Wilcoxon signed rank test (P < .011, z = 2.359) and paired t test (mean difference (95% CI) of 0.60 mm, 0.14-1.05 mm, P < .001). Linear regression analysis was used to test whether peak relative displacement significantly predicted MVC with age as a confounding factor. The model explained 4.6% of the variance (R2 = 0.046, F(2,37) = 0.895, P = .417), and peak relative displacement (β = 0.189, P = .251) did not predict MVC, with age (β = 0.077, P = .638) as a confounding factor. There was a significant interaction of limb*peak tendon displacement (F(1.63-61.92) = 3.958, P = .032) (Figure 2). Bonferroni post hoc analysis showed a significant difference between each of the three most superficial locations, but no differences were found between the four deepest locations in the uninjured limb. However, for the injured limb, there were no significant differences between the majority of locations (Table 1), indicating a more uniform displacement pattern across the injured tendon.

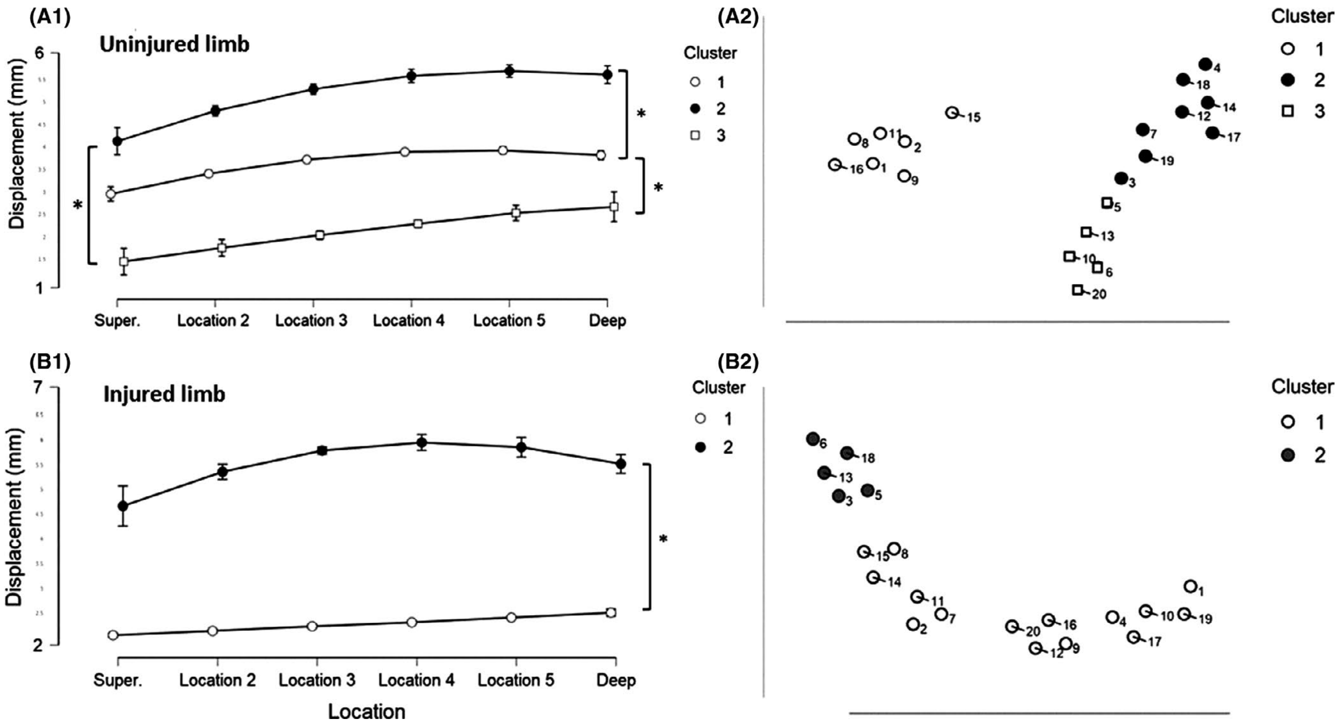

FIGURE 3 Cluster plots based on peak tendon displacements. A-1: mean displacement patterns for the three clusters formed for the healthy limb. A-2: 2D representation of the clusters, whereby each circle represents one patient's data; similar displacement patterns appear close to each other, and dissimilar displacement patterns are further apart in the space. B-1: the displacement patterns for the two clusters found for the injured limb. B-2: Each data point separated into clusters. *Significant difference between groups ($P < .01$)

TABLE 2 Characteristics of the cluster groups (mean ± SD)

Uninjured	Torque at 100% MVC (Nm)	Preferred walking speed (m/s)	Peak relative displacement (mm)	Peak relative displacement (mm) of the other leg
Group 1 (N: 7)	163.9 ± 49.90	1.1 ± 0.25	1.4 ± 1.19	0.5 ± 0.48
Group 2 (N: 8)	185.0 ± 29.12	1.2 ± 0.22	1.0 ± 0.55	0.6 ± 0.64
Group 3 (N: 5)	188.5 ± 44.06	1.1 ± 0.23	1.6 ± 0.78	1.0 ± 0.96
Injured				
Group 1 (N:15)	134.2 ± 39.52	1.2 ± 0.22	0.5 ± 0.34	1.2 ± 0.91
Group 2 (N: 5)	142.4 ± 55.22	1.0 ± 0.30	1.3 ± 1.70	1.4 ± 0.83

3.1 | Clustered groups

For the uninjured limb, the cluster analysis separated subjects into three groups (n = 7, within-cluster sum of squares: 8.40; n = 8, 5.03; n = 5, 5.14; $P < .001$), while only two groups were formed for the injured limb (n = 5, 11.58; n = 15, 25.44; $P < .001$) (Figure 3). There was a significant difference in peak relative displacement ($P = .040$) between injured limb clusters, but not between uninjured limb clusters. There were no significant differences in MVC torque, MVC30% torque, or preferred walking speed in any of the clustered groups for either limb (Table 2). Two-sided paired t test showed significant differences between maximum and minimum displacement for all the uninjured clusters, with mean differences (95% CI) of 1.3 mm (0.29-2.5 mm, $P = .021$) in group 1, 1.1 mm (0.61-1.6 mm, $P < .001$) in group 2, and 1.5 mm (0.18-2.8 mm, $P = .036$) in group 3. For the injured limb clusters, there was a significant difference in group 1, with a mean difference (95% CI) of 0.48 mm (0.29-0.67 mm, $P < .001$), but no significant difference in group 2, mean difference (95% CI) 1.3 mm (0.02-2.6 mm).

3.2 | Maximum and minimum displacement locations

There was no significant difference in maximum mean differences (0.35, 95% CI: 0.38-1.08, $P = .330$) or minimum displacement location (0.10, 0.99-1.19, $P = .850$) between limbs (Figure 4). Uninjured group clusters showed no

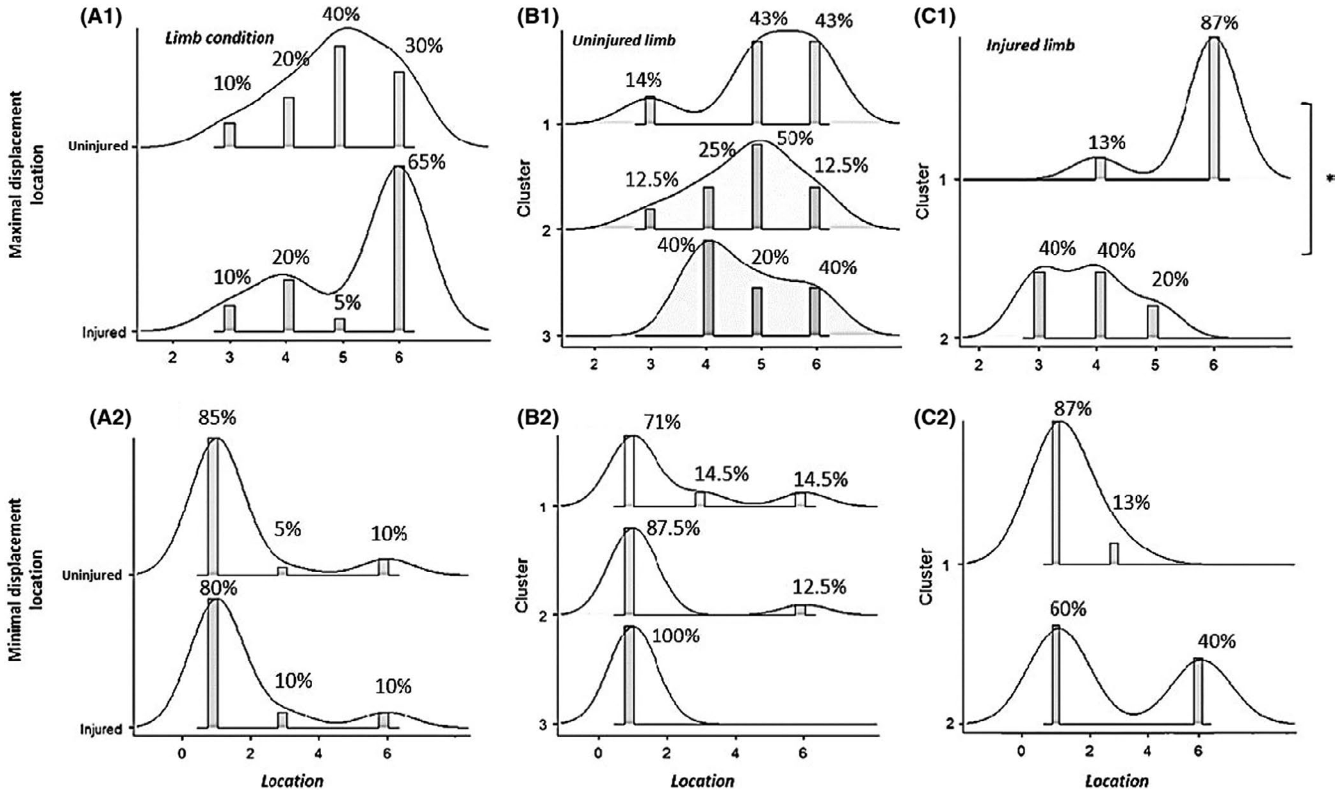

FIGURE 4 Top row: Frequency of maximal displacement location across the tendon for both limbs (A-1), for healthy limb clustered groups (B-1), and for injured limb clustered groups (C-1). Bottom row: Frequency of minimal displacement location across the tendon for both limbs (A-2), for healthy limb clustered groups (B-2), and for injured limb clustered groups (C-2). * Significant difference in maximum displacement location between injured limb clusters ($P < .001$)

statistical differences in maximum or minimum displacement location. In the injured limb clusters, there was a significant difference in maximum displacement location mean difference (1.93, 95% CI: 1.13-2.73, $P < .001$), but no difference in minimum displacement location (1.73, 95% CI: −5.11-1.64, $P = .231$).

4 | DISCUSSION

To our knowledge, this is the first study to investigate within-tendon deformation patterns in non-surgically treated ATR patients, as previous investigations,[20] only included surgically treated patients. We examined patients 14-month post-ATR. As hypothesized, we found evidence of impaired sliding between tendon fascicles originating from different parts of the TS in the injured limb, whereby displacement was more uniform across the width of the injured tendon compared to the uninjured tendon. The impaired tendon internal movement in our non-surgically treated sample has also been observed in surgically treated patients, although it has been suggested that the surgical procedure itself can degrade the gliding properties of the tendon.[20]

At the same absolute plantarflexion torque level, peak relative displacement was ∼32% smaller in the injured limb compared to the uninjured limb. One factor explaining this phenomenon may be a change in the synergistic behavior of plantar flexors in ATR patients. Medial gastrocnemius myotendinous displacement has been reported to decrease post-ATR in multiple studies,[24,25] and deeper flexors such as flexor hallucis longus (FHL) may thus make a bigger contribution to relative plantarflexion force.[26] For example, FHL cross-sectional area has been found to be 5% greater in the injured limb, indicating compensatory hypertrophy.[21] Changes in the motor strategy used to produce plantarflexion torque in the early recovery phase might decrease tensile forces transmitted through the AT, due to a smaller force contribution by the TS. The present results suggest that this compensatory mechanism may be functional for long periods. Although individual motor coordinative strategies vary, the role of FHL in the restoration of function post-ATR should not be neglected.[21]

The impaired displacement observed in the injured limb may have an adverse effect on TS force production and transmission.[20] Our sample showed ~24% plantarflexion strength deficit in the injured limb, highlighting the long-term effects of ATR, which might be a combination of changes in plantar flexor muscle structure,[27,28] and impaired relative displacement between the different parts of the AT.

4.1 | Clustered groups

A novel finding of the present study was that by using unsupervised cluster analysis, we were able to classify AT displacement behavior into three clusters in the uninjured limb whereas only two were identified in the injured limb, which may arise from subject-specific anatomical variations in AT sub-tendons.[11] Subject-specific tendon characteristics are a vital determinant of stress distribution across the tendon,[29,30] which may lead to variation in the location and magnitude of peak displacement within the free AT. However, in spite of any individual differences, the phenomenon of non-uniform displacement between independent tendon fascicles across the AT was evident in all of the uninjured clusters, further supporting the idea that this is a sign of healthy tendon function.[16,19]

For the injured limb, patients within both clusters showed an impaired displacement pattern. The first group, which included the majority of patients, showed low peak displacement. However, there was a difference between maximum and minimum displacement, indicating some degree of non-uniformity. The second group had similar peak displacement between the injured and uninjured limbs, but there was a more uniform displacement pattern across the injured tendon. Thus, in general, the mechanical sliding of fascicles within the tendon was impaired in our non-surgically treated patients 14-months post-ATR. Interfascicular matrix adhesion might be one reason for the limited inter-fascicle sliding.[19]

Differential displacement in the injured tendon may arise from subject-specific anatomical differences of tendon and its twisting pattern. There was a significant difference in maximal displacement location, whereby group 2 showed a more superficial location compared to a deeper location in group 1 (Figure 4). These differences in behavior may reflect differences in underlying anatomy, although this cannot be confirmed. Alternatively, tendon healing may have caused alterations in normal twisting of the tendon fascicles and consequently affected the displacement pattern.

On average, maximal displacement was observed at location 5 for the uninjured limb and the deepest location for the injured limb. Thus, both limbs showed higher displacement in the deep region of the tendon, whereas minimal displacement occurred at the most superficial part in both limbs, despite the injury. However, patients in different clusters showed different patterns and locations of maximal displacement across the tendon. Such individual differences highlight the importance of personalized diagnostic and treatment approaches.

The present study suggests that non-surgical treatment leads to impairments regarding non-uniform displacement of the tendon. However, some patients in the second cluster group might have regained a normal tendon displacement 14 month post-rupture. Previously, non-uniformity in tendon displacement has been investigated in surgically treated patients. Similarly to the present study, the study of Fröberg et al showed more uniform displacement within the ruptured tendon during active dorsiflexion (0.3 vs 3.3 mm difference between deep and superficial).[20] Future studies are required to investigate whether the treatment or rehabilitation protocol would have an effect on the displacement pattern of the tendon post-rupture.

There are some limitations of this study. One limitation is that only one proximal-distal location of the tendon was investigated. The probe was placed on the most distal portion of the tendon, as tears might have occurred on a more proximal level. However, as established before, fascicles function independently,[13] thus any tear on an upper level would have an adverse effect on the gliding of the fascicles relative to each other. The area investigated is typically the investigated region[16-18,20] where biochemical composition may facilitate greater sliding between fascicles.[31] The small sample size was not enough to identify the factors affecting tendon displacement patterns and AT recovery, or to confirm whether different displacement patterns are associated with functional recovery.

5 | CONCLUSION

We found three distinct patterns of AT displacement during isometric plantarflexion in the uninjured limb and two in the injured limb. These patterns may arise from subject-specific anatomical variations in AT sub-tendons, which may be modified due to the injury. Subject-specific tendon characteristics are a vital determinant of stress distribution across the tendon, which may in turn lead to variations in the location and magnitude of peak displacement within the free AT. Quantifying internal tendon displacement patterns after ATR provides new insights for evaluation of the recovery of Achilles tendon.

6 | PERSPECTIVE

In studies of post-rupture tendon function, group mean values are typically reported, which may ignore patient-specific recovery patterns.[16,20] Here, we examined whether Achilles tendon internal displacement patterns could be classified in order to better understand good recovery. Our results clearly indicate the necessity to consider the variations in

AT sub-tendon anatomy among the population, and hence, the importance of introducing personalized diagnostic and treatment approaches. The results also show that some non-surgically treated patients can recover healthy tendon displacement patterns by 14 months post-rupture, but the majority of patients showed impaired tendon displacement compared to the uninjured limb. Future studies that aim to find optimal treatment approaches post-ATR should consider the possibility that the surgical trauma itself may affects tendon gliding properties and compare between different treatments protocols.[20]

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CONFLICT OF INTEREST

The authors declare that they have no competing interests.

ORCID

Ra'ad M. Khair https://orcid.org/0000-0002-3226-8840
Lauri Stenroth https://orcid.org/0000-0002-7705-9188
Taija Finni https://orcid.org/0000-0002-7697-2813

REFERENCES

1. Ganestam A, Kallemose T, Troelsen A, Barfod KW. Increasing incidence of acute Achilles tendon rupture and a noticeable decline in surgical treatment from 1994 to 2013. A nationwide registry study of 33,160 patients. *Knee Surg Sports Traumatol Arthrosc*. 2016;24(12):3730-3737.
2. Lantto I, Heikkinen J, Flinkkilä T, Ohtonen P, Leppilahti J. Epidemiology of Achilles tendon ruptures: increasing incidence over a 33-year period. *Scand J Med Sci Sports*. 2015;25(1):e133-e138.
3. Möller M, Kälebo P, Tidebrant G, Movin T, Karlsson J. The ultrasonographic appearance of the ruptured Achilles tendon during healing: a longitudinal evaluation of surgical and nonsurgical treatment, with comparisons to MRI appearance. *Knee Surg Sports Traumatol Arthrosc*. 2002;10(1):49-56.
4. Olsson N, Silbernagel KG, Eriksson BI, et al. Stable surgical repair with accelerated rehabilitation versus nonsurgical treatment for acute Achilles tendon ruptures: a randomized controlled study. *Am J Sports Med*. 2013;41(12):2867-2876.
5. Soroceanu A, Sidhwa F, Aarabi S, Kaufman A, Glazebrook M. Surgical versus nonsurgical treatment of acute Achilles tendon rupture: a meta-analysis of randomized trials. *J Bone Joint Surg Am*. 2012;94(23):2136-2143.
6. van der Eng DM, Schepers T, Goslings JC, Schep NWL. Rerupture rate after early weightbearing in operative versus conservative treatment of Achilles tendon ruptures: a meta-analysis. *J Foot Ankle Surg Off Publ Am Coll Foot Ankle Surg*. 2013;52(5):622-628.
7. Aufwerber S, Heijne A, Edman G, Silbernagel KG, Ackermann PW. Does early functional mobilization affect long-term outcomes after an achilles tendon rupture? A randomized clinical trial. *Orthop J Sports Med*. 2020;8(3):2325967120906522.
8. McCormack R, Bovard J. Early functional rehabilitation or cast immobilisation for the postoperative management of acute Achilles tendon rupture? A systematic review and meta-analysis of randomised controlled trials. *Br J Sports Med*. 2015;49(20):1329-1335.
9. Zhao J-G, Meng X-H, Liu L, Zeng X-T, Kan S-L. Early functional rehabilitation versus traditional immobilization for surgical Achilles tendon repair after acute rupture: a systematic review of overlapping meta-analyses. *Sci Rep*. 2017;7(1):1-7.
10. Barfod KW, Hansen MS, Hölmich P, Kristensen MT, Troelsen A. Efficacy of early controlled motion of the ankle compared with immobilisation in non-operative treatment of patients with an acute Achilles tendon rupture: an assessor-blinded, randomised controlled trial. *Br J Sports Med* 2020;54(12):719-724.
11. Edama M, Kubo M, Onishi H, et al. The twisted structure of the human A chilles tendon. *Scand J Med Sci Sports*. 2015;25(5):e497-e503.
12. Finni T, Bernabei M, Baan GC, Noort W, Tijs C, Maas H. Non-uniform displacement and strain between the soleus and gastrocnemius subtendons of rat Achilles tendon. *Scand J Med Sci Sports*. 2018;28(3):1009-1017.
13. Haraldsson BT, Aagaard P, Qvortrup K, et al. Lateral force transmission between human tendon fascicles. *Matrix Biol*. 2008;27(2):86-95.
14. Bojsen-Møller J, Hansen P, Aagaard P, Svantesson U, Kjaer M, Magnusson SP. Differential displacement of the human soleus and medial gastrocnemius aponeuroses during isometric plantar flexor contractions in vivo. *J Appl Physiol*. 2004;97(5):1908-1914.
15. Beyer R, Agergaard A-S, Magnusson SP, Svensson RB. Speckle tracking in healthy and surgically repaired human Achilles tendons at different knee angles—A validation using implanted tantalum beads. *Transl Sports Med*. 2018;1(2):79-88.
16. Slane LC, Thelen DG. Non-uniform displacements within the Achilles tendon observed during passive and eccentric loading. *J Biomech*. 2014;47(12):2831-2835.
17. Arndt A, Bengtsson A-S, Peolsson M, Thorstensson A, Movin T. Non-uniform displacement within the Achilles tendon during passive ankle joint motion. *Knee Surg Sports Traumatol Arthrosc*. 2012;20(9):1868-1874.
18. Stenroth L, Thelen D, Franz J. Biplanar ultrasound investigation of in vivo Achilles tendon displacement non-uniformity. *Transl Sports Med*. 2019;2(2):73-81.
19. Thorpe CT, Udeze CP, Birch HL, Clegg PD, Screen HR. Capacity for sliding between tendon fascicles decreases with ageing in injury prone equine tendons: a possible mechanism for age-related tendinopathy. *Eur Cell Mater*. 2013;25(4).
20. Fröberg Å, Cissé A-S, Larsson M, et al. Altered patterns of displacement within the Achilles tendon following surgical repair. *Knee Surg Sports Traumatol Arthrosc*. 2017;25(6):1857-1865.
21. Heikkinen J, Lantto I, Piilonen J, et al. Tendon length, calf muscle atrophy, and strength deficit after acute Achilles tendon rupture: long-term follow-up of patients in a previous study. *JBJS*. 2017;99(18):1509-1515.
22. Reito A, Logren H-L, Ahonen K, Nurmi H, Paloneva J. Risk factors for failed nonoperative treatment and rerupture in acute Achilles tendon rupture. *Foot Ankle Int*. 2018;39(6):694-703.
23. Surgeons AA of O. The diagnosis and treatment of acute Achilles tendon rupture: guideline and evidence report. *Rosemt IL Am Acad Orthop Surg*. 2009.

24. Finni T, Hodgson JA, Lai AM, Edgerton VR, Sinha S. Nonuniform strain of human soleus aponeurosis-tendon complex during submaximal voluntary contractions in vivo. *J Appl Physiol*. 2003;95(2):829-837.
25. De la Fuente CI, Lillo RP, Ramirez-Campillo R, et al. Medial gastrocnemius myotendinous junction displacement and plantar-flexion strength in patients treated with immediate rehabilitation after Achilles tendon repair. *J Athl Train*. 2016;51(12):1013-1021.
26. Finni T, Hodgson JA, Lai AM, Edgerton VR, Sinha S. Muscle synergism during isometric plantarflexion in achilles tendon rupture patients and in normal subjects revealed by velocity-encoded cine phase-contrast MRI. *Clin Biomech*. 2006;21(1):67-74.
27. Baxter JR, Farber DC, Hast MW. Plantarflexor fiber and tendon slack length are strong determinates of simulated single-leg heel raise height. *J Biomech*. 2019;86:27-33.
28. Hullfish TJ, O'Connor KM, Baxter JR. Medial gastrocnemius muscle remodeling correlates with reduced plantarflexor kinetics 14 weeks following Achilles tendon rupture. *J Appl Physiol Bethesda Md 1985*. 2019;127(4):1005-1011.
29. Hansen W, Shim VB, Obst S, Lloyd DG, Newsham-West R, Barrett RS. Achilles tendon stress is more sensitive to subject-specific geometry than subject-specific material properties: A finite element analysis. *J Biomech*. 2017;56:26-31.
30. Shim VB, Fernandez JW, Gamage PB, et al. Subject-specific finite element analysis to characterize the influence of geometry and material properties in Achilles tendon rupture. *J Biomech*. 2014;47(15):3598-3604.
31. Sun Y-L, Wei Z, Zhao C, et al. Lubricin in human achilles tendon: The evidence of intratendinous sliding motion and shear force in achilles tendon. *J Orthop Res*. 2015;33(6):932-937.

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