Foot and Ankle Surgery 25 (2019) 529–533

Contents lists available at ScienceDirect

Foot and Ankle Surgery

journal homepage: www.elsevier.com/locate/fas

Alterations in structure of the muscle-tendon unit and gait pattern after percutaneous repair of Achilles tendon rupture with the Dresden instrument

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ARTICLE INFO

Article history:
Received 2 September 2017
Received in revised form 5 April 2018
Accepted 9 April 2018

Keywords:
Achilles tendon rupture
Gait analysis
Tendon lengthening
Muscle atrophy
Functional deficits
Minimally invasive Achilles tendon repair

ABSTRACT

Background: Functional deficits after Achilles tendon (AT) ruptures are observed. The relationship between musculotendinous structural alterations and functional outcome is not clear.
Methods: Kinematic analyses (level walking, stair climbing), patient-reported outcome measures (PROMs), calf atrophy (maximum calf circumference (MCC)), and AT length were evaluated in patients after percutaneous AT repair with the Dresden instrument (n = 20 min. follow-up: 24 months).
Results: Patients achieved good results in PROMs. However, MCC decreased significantly and AT length increased significantly postoperatively. Side-to-side MCC differences over 2 cm resulted in significantly lower PROMs. AT lengthening correlated with increased dorsiflexion and decreased plantarflexion.
Conclusion: Calf atrophy and AT lengthening after minimally invasive AT repair resulted in inferior ankle kinematics and PROMs.

1. Introduction

The operative treatment of acute Achilles tendon rupture (ATR) has two goals: besides avoiding complications like AT re-rupture, sural nerve lesions and wound healing problems, a complete functional recovery and return to sportive activity are the goals of both the patient and the surgeon. By introducing a percutaneous suture technique in 1977, Ma and Griffith seemed to overcome these complications with satisfying restoration of tendon length and continuity in their cadaver experiments [1]. However, studies that followed, failed to reproduce these results: the rate of reported sural nerve lesions was up to 10% [2,3], while tendon gapping and maladaptation was found in four out of five specimens in cadaver experiments [4]. Since then, several modifications of percutaneous or minimal-invasive techniques have been described [5–10], in which the risk of sural nerve entrapment was considerably reduced.

However, minimal-invasive techniques for AT repair were still under debate as Hockenbury and Johns reported on tendon maladaptation and reduced tensile strength compared to open repair [4]. Although experimental cadaver studies *per se* do not reflect the clinical situation and disregard the biology of tendon healing, suture techniques and materials (absorbable versus non-absorbable) have been tested in cadaver studies to examine any tendon gap formation and the pull-out strength [3,11–15]. Recent biomechanical studies showed comparable [11] or even higher resistance to tensile strength after open tendon repair according to the Dresden technique compared to open double Kessler suture configuration [16].

The existing treatment options for acute ATR deliver acceptable results in terms of clinical outcome [17–19], but functional deficits, such as reduced heel rise height [20–22] and reduced peak plantarflexion torque [23,24], are still observed.

The reasons for these deficits are not clear. AT lengthening and impairment of the muscular properties of the triceps surae muscle are potential factors. AT lengthening was described nearly 35 years ago during the early postoperative mobilization phase after open repair [25]. Several studies confirmed this finding after open AT suture [22,26–28], after conservative, as well as, after minimally invasive therapy. A reduced maximum calf circumference (MCC) of up to 6 %, reduced calf muscle volume, and fatty degeneration of the triceps surae were described after ATR compared to the non-involved, contralateral side [23,24,29,30]. However, the exact impact of these structural alterations on subjective (patient-reported outcome measures (PROMs)) and

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https://doi.org/10.1016/j.fas.2018.04.004
1268-7731/

objective outcomes (gait analysis) of ATR patients is not clear [22,27].

The present study examined the structural alterations of the tendon-muscle unit after minimally invasive treatment of ATR and evaluated the impact on subjective PROMs and objective functional outcome (ankle kinematics).

2. Methods

2.1. Patients

Twenty patients (16 males, 4 females; mean age 45.6 ± 12 years, range 24–63 years) with an average follow-up of 43.5 ± 12 months (range 27–69 month) after percutaneous AT repair for acute ATR were randomly selected from the electronic database of our institute. Inclusion criteria were: percutaneous AT repair, age over 18 years and a minimum follow-up of 24 months (single surgeon series (SM)). Patients with additional injuries of the affected or contralateral lower extremity were excluded, as well as, patients with previous cortisone, fluoroquinolones with manifested tendinopathy or anabolic steroid medication or other relevant comorbidities, like rheumatoid arthritis. The local ethics committee authorized the study (No EA/2/095/11), which was performed in accordance with the ethical standards of the Declaration of Helsinki. Patients gave written informed consent prior to participation.

All patients exhibited acute (<10 days) ATR and underwent a percutaneous suture technique using the Dresden instrument [10,31]. A 2 cm skin incision at the medial border of the Achilles tendon was made approximately 5 cm proximal to rupture site. Following fasciotomy, the Dresden instrument was inserted subfascially, while preserving the underlying paratenon intact. Both instruments are advanced as close to the tendon insertion as possible. One is placed medial, the other lateral to the distal tendon stump. A straight needle armed with resorbable PDS-II No.1 (polydioxanon, PDS-II No.1; Ethicon® Johnson–Johnson) was pierced through the skin-instrument-tendon-instrument-skin. This step was repeated with a second suture, before both needles were removed. Instruments were pulled back so that PDS-sutures were diverted through the proximal incision. Pull-out-strength of the sutures was tested thoroughly. Finally, minimal-invasive AT repair was completed by a Krackow locking stitch in the proximal tendon stump. Knotting was completed, but in contrast to the original described technique [31], ATR was secured in an over-tightened manner.

Postoperatively, early functional rehabilitation was initiated. The foot was placed in a walker with 30° of plantarflexion for six weeks. Partial weight bearing on crutches was allowed to 15 kg. Heel height was reduced 10° per week after six weeks, and weight-bearing was increased, as tolerated. Patients were allowed to walk in a normal shoe at the beginning of the ninth postoperative week. Physiotherapy was initiated two weeks after surgery and supervised for twelve weeks. Physiotherapy consisted of functional training of the muscles and proprioceptive, as well as, coordinative training. Plantarflexion exercises started after the third week and were limited to neutral position.

2.2. Clinical follow-up

Patients' subjective outcome was measured using the Hannover score (maximum: 100 points) [32], and Achilles Tendon Rupture Score (ATRS (maximum: 100 points)) [33], which are ATR-specific scales. Pain intensity and functional limitation were evaluated using a visual analogue scale (VAS_{pain}: 0 = no and 10 = greatest assumable pain; VAS_{func}: 0 = no and 10 = greatest assumable functional limitation). Levels of pre- and post-injury sports activity were assessed using the Tegner activity score (maximum: 10 points for professional sport). Patients with reduced sports activities were asked to provide reasons for the reduced activity. Maximum calf circumference (MCC) was measured bilaterally 15 cm below the medial knee joint line. Passive ankle ROM (dorsiflexion–plantarflexion) was measured using a goniometer on both ankles.

2.3. Ankle and subtalar kinematics

Bipedal gait is a complex motion sequence that involves multiple interacting parameters. However, an intact and physiological muscle-tendon unit is necessary for forward propulsion, which may deteriorate after ATR. Gait analysis was used to detect altered ankle and subtalar kinematics during daily activities, such as level ground walking and stair climbing. Dorsiflexion, plantarflexion, and full ankle ROM measured ankle kinematics. Eversion, inversion and full subtalar ROM measured subtalar kinematics.

A motion capture system consisting of ten infrared cameras (MX-T20 System, VICON, Oxford, UK) recorded the kinematic data (120 Hz) of the lower extremities as each subject walked barefoot at a self-selected comfortable speed (mean: 1.21 m/s; range: 0.89–1.52) along a marked 10-m pathway. A set of twenty-two spherical reflective skin markers was secured using double-sided tape on the following prominent bony landmarks: greater trochanter, medial and lateral knee joint space, tibial tuberositas, medial and lateral malleolus, posterior heel, distal part of the first and fifth metatarsals, and between the distal heads of the second and third metatarsals. Static trials were performed prior to each measurement to calibrate the system and determine the initial neutral angle of the ankle in a standing position. A minimum of five walking trials was performed for each subject. Further kinematic data were collected in the same laboratory during stair climbing (upstairs and downstairs) on a custom four-step staircase.

Kinematic data from all activities were processed after collection, using customized scripts developed in the MATLAB environment (Mathworks Inc., Natick, MA, U.S.A.). A joint coordinate system was used as recommended by the International Society of Biomechanics (ISB) [34,35] to assess ankle movement. Absolute angles were calculated via comparison to the initial static trial to determine the neutral angle of both ankles. Range of motion (ROM) in the sagittal plane (dorsiflexion–plantarflexion) and frontal plane (eversion–inversion) was calculated for each trial as the difference between maximum plantarflexion and maximum dorsiflexion and maximum eversion and maximum inversion, respectively.

2.4. Sonographic tendon length measurements

Real-time, B-mode, two-dimensional ultrasonography was used to non-invasively measure the AT length in operated and contralateral limbs. A 10-cm, 7.5-MHz ultrasound probe (My Lab 60, Esaote S.p.A., Genoa, Italy) was secured at the musculotendinous junction (MTJ) of the Achilles tendon and the medial gastrocnemius muscle. A skin marker visualized the exact MTJ location. The length from the calcaneal insertion point to the MTJ point was calculated using customized MATLAB programs.

2.5. Statistics

The normality of all parameters was tested using the Shapiro-Wilk test in SPSS (IBM, Armonk, NY, U.S.A.). A two-tailed dependent, paired-sample *t-test* (for normally distributed data) or two-tailed Wilcoxon signed-rank test (for non-normally distributed data) were used for intra-patient comparisons. Intra-patient changes in AT length, MCC and ankle angle parameters were calculated as the difference between parameter values on the operated (OP) side minus the contralateral (CON) side and as relative values in percentages (ratio: OP/CON × 100). A one-tailed Spearman test was used for bivariate correlations. A significance of $p < 0.05$ was set for all statistical calculations. Normally distributed data are presented as the means ± standard deviations. Non-normally distributed data are presented as medians with ranges.

3. Results

3.1. Clinical follow-up

The mean ATRS at follow-up was 86 ± 11 points (range 55–100), and the Hannover score was 82 ± 7 points (range 64–91). VAS for pain and functional limitations was rated as low (median VAS_{pain} 0 (range 0–2.9); median VAS_{func} 1.1 (range 0–3.4)). However, more than half of the patients (11 out of 20; 55%) did not reach the same pre-injury physical activity level ($p = 0.002$). Patients retrospectively scored their pre-injury activity levels (Tegner activity score) as 5.5 ± 1.5 (range 2–8) and their current activity level as 4.7 ± 1.6 (range 1–8) at follow-up examinations. The reported reasons for a reduced activity level included fear of re-rupture (3 out of 11), lack of interest in sports activities due to other daily priorities (5 out of 11), and subjective functional impairment after AT repair (3 out of 11). Patients were evaluated at different follow-up times with a wide range of 27–82 months, but no significant correlation was found between PROMs and follow-up duration.

The MCC of the operated side was significantly lower compared to the contralateral side (36.5 ± 3.0 cm vs. 38.3 ± 2.4 cm, $p < 0.001$; relative value mean: 95 ± 5%, range 84–104 %). The mean side-to-side difference of MCC was 1.6 ± 1.7 cm. Passive ankle ROM using a goniometer revealed no significant differences between the operated and contralateral ankles (dorsiflexion: 15 ± 1° vs. 16 ± 1°, $p = 0.06$; plantarflexion: 39.0 ± 1° vs. 42 ± 2°, $p = 0.45$).

3.2. Ankle and subtalar kinematics

The average maximum dorsiflexion during level walking was significantly higher on the operated side compared to the contralateral ankle ($p < 0.001$). The average maximum plantarflexion and full ankle ROM were significantly lower on the operated compared to the contralateral ankle ($p < 0.001$). No significant differences were observed in subtalar inversion or eversion in the frontal plane (Table 1).

Ankle plantarflexion during stair climbing (upstairs and downstairs) was significantly lower on the operated side (upstairs: $p = 0.006$; downstairs: $p = 0.029$). Full ankle ROM was significantly reduced on the operated side ($p = 0.025$) when walking downstairs (Table 1).

3.3. Achilles tendon length

The sonographically measured AT length was significantly longer on the operated side ($p = 0.009$; 213.3 ± 29.4 mm vs. 198.5 ± 21.8 mm; relative value mean: 107.5 ± 11%, range: 81.5–121.9%) (Table 2).

3.4. Correlations

PROMs exhibited a significant negative correlation with a side-to-side difference in MCC (Table 3). A series of comparisons based on the clinically relevant threshold of 0.5 cm for the MCC side-to-side difference was performed (from 0.5 cm to 3.0 cm). Significantly lower scoring results were observed in patients, when the MCC exceeded 2 cm in side-to-side difference (ATRS: 90.6 vs. 78.2 points, $p = 0.026$; Hannover score: 84.9 vs. 75.3 points, $p = 0.025$; Tegner score postoperative: 5.4 vs. 3.8, $p = 0.01$), and increased functional limitations on the VAS_{funct} were reported (0.8 vs. 2.3 points, $p = 0.01$). Side-to-side difference in MCC negatively correlated with intra-patient differences in maximum ankle ROM during downstairs walking ($r = -0.437$; $p = 0.027$).

Altered tendon length did not correlate with PROMs as absolute or relative values (OP/CON side). However, a correlation between MCC difference and AT length difference was observed (Table 3).

Intra-patient differences in AT length positively correlated with side-to-side differences in dorsiflexion ($r = 0.428$, $p = 0.034$) and negatively correlated with plantarflexion ($r = -0.435$, $p = 0.028$) as measured biomechanically during level walking. Differences in AT length correlated with intra-patient differences in eversion ($r = 0.441$, $p = 0.026$) and inversion ($r = -0.385$, $p = 0.047$) during upstairs walking (subtalar kinematic). In contrast, AT length did not exhibit similar correlations in clinically measured ROM using the goniometer.

Table 1
The mean (SD) of maximum three-dimensional ankle angles and ranges of motion (ROM) during gait and stair descent (*t*-test/Wilcoxon related samples) (OP: operated side, i.e., Achilles tendon rupture side; CON: contralateral; DF: dorsiflexion, PF: plantarflexion).

Level Walking	Parameter	OP side	CON side	p
Sagittal	Dorsiflexion	10.9 ± 2.4	9.7 ± 3.2	< **0.001***
	Plantarflexion	19.3 ± 7.0	22.9 ± 5.5	< **0.001***
	DF/PF-ROM	30.1 ± 7.8	32.5 ± 5.8	< **0.001***
Frontal	Inversion	4.3 ± 3.0	5.9 ± 3.1	0.062
	Eversion	8.6 ± 3.5	6.4 ± 3.1	0.086
	Inv/Ev-ROM	13.0 ± 3.1	12.4 ± 2.6	0.328
Stair ascent	**Parameter**	**OP side**	**CON side**	**p**
Sagittal	Dorsiflexion	13.9 ± 3.5	12.2 ± 5.1	0.091
	Plantarflexion	19.6 ± 5.8	23.7 ± 4.6	**0.006***
	DF/PF- ROM	33.5 ± 7.0	35.9 ± 5.5	0.167
Frontal	Inversion	2.1 ± 3.4	4.2 ± 6.9	0.145
	Eversion	6.3 ± 3.8	4.8 ± 7.7	0.575
	Inv/Ev- ROM	8.4 ± 2.9	9.0 ± 4.2	0.852
Stair descent	**Parameter**	**OP side**	**CON side**	**p**
Sagittal	Dorsiflexion	21.3 ± 5.1	22.3 ± 6.4	0.407
	Plantarflexion	27.8 ± 7.0	31.4 ± 5.2	**0.029***
	DF/PF- ROM	49.1 ± 9.0	53.6 ± 6.6	**0.025***
Frontal	Inversion	± 3.5	6.9 ± 7.8	0.940
	Eversion	4.9 ± 4.8	6.4 ± 6.4	0.575
	Inv/Ev- ROM	12.6 ± 5.5	13.2 ± 5.1	0.709

4. Discussion

Functional deficits after ATR are a known problem after both conservative and operative treatment [24,30,36]. These deficits may lead to restrictions in everyday life and an inability to return to pre-injury activity levels [37,38]. The current literature lacks a differential cause-analysis of these functional deficits.

This report is the first study to show significant correlations between Achilles tendon lengthening after AT repair, and MCC and ankle kinematics, such as the active ankle extension-flexion, during daily activities. Calf muscle atrophy was highly related to PROMs and subjective functional limitations. PROMs were significantly reduced when MCC exceeded 2 cm in side-to-side differences, which indicates that calf atrophy was related to a worse clinical outcome.

We did not find any correlation between clinically measured ankle ROM and increased tendon length after ATR, which is consistent with previous studies [23,27]. However, detailed gait analysis facilitated a more precise examination of ankle ROM in our study. Gait analysis was based on a motion capture system and revealed a significant increase in dorsiflexion and decrease in

Table 2
Data of maximum calf circumference and Achilles tendon length (OP: operated side, i.e., Achilles tendon rupture side; CON: contralateral).

	OP side mean ± SD	CON side mean ± SD	OP side range (min-max)	CON side range (min-max)	p
Maximum calf circumference (cm)	36.5 ± 3.0	38.3 ± 2.4	29.5–42	34.5–42	<0.001
Achilles tendon length (mm)	213.3 ± 29.4	198.5 ± 21.8	137.8–269	153.5–263.8	0.009

Table 3
Correlations of clinical scores and difference in maximum calf circumference and Achilles tendon length (VAS_{funct}: visual analogue scale for functional limitation, ATRS: Achilles Tendon Rupture Score, MCC: maximum calf circumference, AT: Achilles tendon, n.s.: not significant; significance $p < 0.05$).

	ATRS	Hannover score	Tegner score postop	VAS_{funct}	MCC difference	AT length difference
ATRS		r = 0.62; p = 0.004	r = 0.58; p = 0.008	r = −0.51; p = 0.02	r = −0.58; p = 0.004	n.s.
Hannover score	r = 0.62; p = 0.004		r = 0.71; p < 0.0001	r = −0.64; p = 0.003	r = −0.57; p = 0.003	n.s
Tegner score postop	r = 0.58; p = 0.008	r = 0.71; p < 0.0001		r = −0.54; p = 0.01	r = −0.57; p = 0.005	n.s
VAS_{funct}	r = −0.51; p = 0.02	r = −0.64; p = 0.003	r = −0.54; p = 0.01		r = 0.58; p = 0.004	n.s
MCC difference	r = −0.58; p = 0.004	r = −0.57; p = 0.003	r = −0.57; p = 0.005	r = 0.58; p = 0.004		r = 0.59; p = 0.008
AT length difference	n.s	n.s	n.s	n.s	r = 0.59; p = 0.008	

plantarflexion and total ankle ROM on the operated side during level walking. Plantarflexion was significantly reduced in stair climbing (upstairs and downstairs walking) and full ankle ROM during stair descent. In contrast to clinically passive ROM, a significant positive correlation was found between AT lengthening and dorsiflexion, and a negative correlation was observed with plantarflexion during level walking.

Besides restored tendon length, muscular rehabilitation is also essential for full motor function. Several studies reported muscular atrophy after ATR [23,29,39]. A high correlation between MCC and peak plantar flexion torque was also found. Clinically measured calf circumference was recommended as a predictor of functional outcome based on these findings [30]. Our results demonstrated a significant reduction in PROMs when MCC exceeded 2 cm in side-to-side difference. Whether the reduction of MCC is a consequence of the lengthening of the AT, and thus, indirectly plays a role in the ankle deficit or it is itself an isolated added phenomenon that worsens the function remains still an open question for future studies.

Although we over-tighten the AT during AT repair, we still found a significant increase in AT length after ATR. This finding could be possibly attributed to the surgical technique itself, to the absorbable sutures used, or even to a tendon remodeling after initiation of motion. The exact reasons could be examined in future studies. Regardless of this, AT lengthening is a relevant clinical problem, as increased AT length results in persistent plantar flexion strength deficits [40].

Moreover, deficits in neuromuscular innervation or the loss of muscular initial tension may generally explain muscular atrophy, which was demonstrated in experimental denervation and tenotomy in animal models [41–44]. The length of the originally tensed triceps surae muscle must decrease, when Achilles tendon length increases in an equal amount [45], which means a loss in the initial tension of the triceps surae muscle and a shortening of its fiber length. Maganaris demonstrated that the relative muscle force of the soleus was reduced with as little as a 0.5 cm difference in fiber length [46]. Suydam et al. used fiber length/muscle force diagrams and demonstrated that a higher activation level of the muscle is needed to recruit more muscle fibers and produce the same amount of force when fiber length is reduced. They found increased triceps surae activation in patients with AT lengthening during level ground walking [45]. These authors postulated that the enhanced muscle activity indicated that calf muscle activation during gait was not impaired, and therefore, this alteration was not responsible for muscle atrophy. They interpreted the increased triceps surae activation as a compensatory mechanism to overcome increased AT length [45].

However, if lengthening of the muscle-tendon unit after ATR surmounts intrinsic compensatory mechanisms, such as the capacity of increased fiber activation, then muscular atrophy may emerge [47] and additional compensatory mechanisms, such as hypertrophy of deep flexors (e.g., flexor digitorum longus or flexor hallucis longus), may be observed [39].

There are three limitations on this study. First of all, as we did not include patients after open operative AT repair or conservative therapy, a control group is lacking in our study design. Thus, the non-involved contralateral side had to serve as an internal control. Although we are presenting relevant relationships between structural alterations of the tendon-muscle unit and clinical, as well as, functional outcome data, these results refer to the Dresden technique exclusively and in a strict sense are not transferable to other minimal-invasive techniques. Secondly, this is a retrospective study with a relatively small population with a relatively wide range of age with an inevitable recall bias for estimating the pre-injury activity levels, so care should be taken in interpreting the postoperative activity level and the ATR-recovery. Finally, our rehabilitation protocol was more restrictive compared to recommended ones after open AT repair [48–51], which might have influenced negatively MCC and ankle ROM in our study. In a meta-analysis published by Braunstein et al. in 2015, full-weight bearing and early ankle ROM were recommended as rehabilitation protocol after minimal-invasive AT repair [52]. A more aggressive rehabilitation program might potentially improve the functional outcome without leading to an increased AT lengthening.

5. Conclusion

Achilles tendon lengthening significantly correlated with ankle ROM in ground level walking and calf muscle atrophy, which was significantly related to clinical outcome scores and subjective functional limitations. Calf atrophy that exceeded 2 cm in side-to-side comparisons correlated with a significant reduction in clinical outcome scores. Therefore, a threshold of 2 cm in side-to-side differences may be a possible indicator for a clinically impaired outcome.

Conflict of interest

The authors declare that no conflict of interest exists.

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