Long-term biomechanical outcomes after Achilles tendon ruptures

Claudio Rosso · Daniel M. Buckland · Caroline Polzer ·
Patrick Sadoghi · Reinhard Schuh · Lukas Weisskopf ·
Patrick Vavken · Victor Valderrabano

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Abstract

Purpose The ideal treatment for Achilles tendon ruptures is still unknown. Biomechanical were correlated to radiological and clinical parameters to study outcomes.

Methods In this retrospective, assessor-blinded multi-centre cohort study, 52 patients with unilateral Achilles tendon rupture were assessed, each at least 3 years after injury. Patients underwent open surgery, percutaneous surgery or non-surgical treatment of Achilles tendon rupture. Both legs underwent plantar pressure distribution and isokinetic measures. Demographic parameters, maximum calf circumference (MCC) and clinical scores (American Orthopaedic Foot and Ankle Society, Achilles tendon

rupture score, Hannover) were also evaluated. Complications were not assessed.

Results Peak plantar flexion torque (PPFT) was significantly weaker on the treated side compared to the untreated leg [80.4 ± 29.7 Nm (mean $\pm$ SD) vs. 92.1 ± 27.4 Nm, $p < 0.0001$]. PPFT and push-off force (POFF) were not different between treatment groups nor was there a leg difference in POFF alone. There was only a weak correlation of clinical scores and PPFT or POFF, respectively. MCC correlated significantly with both PPFT ($R^2 = 0.21$, $p = 0.01$) and POFF ($R^2 = 0.29$, $p < 0.0001$). POFF appeared to be a predictor of PPFT ($R^2 = 0.31$, $p < 0.0001$). Open surgery outperformed non-surgical treatment in terms of centre-of-pressure line ($p = 0.007$), torque per muscle volume ($p = 0.04$) and relative POFF per body weight ($p = 0.02$) and relative in side comparison ($p = 0.03$).

Conclusions Clinical scores do not predict biomechanical outcomes. Clinically measured MCC is a good predictor of PPFT and POFF and can easily be used in clinical practice. Relative POFF in side comparison as well as per body weight favours surgical treatment.

Keywords Peak plantar flexion torque · COP · Achilles tendon rupture · Plantar pressure distribution (PPD)

C. Rosso (✉) · D. M. Buckland · C. Polzer · P. Vavken ·
V. Valderrabano

Orthopaedic Department, University Hospital Basel, University
of Basel, Spitalstrasse 21, 4031 Basel, Switzerland
e-mail: Claudio.Rosso@unibas.ch

P. Sadoghi
Department of Orthopaedic Surgery, Medical University Graz,
Graz, Austria

R. Schuh
Department of Orthopaedics, Vienna General Hospital,
Medical University of Vienna, Vienna, Austria

L. Weisskopf
Rennbahn Clinic, Muttentz, Switzerland

P. Vavken
Harvard Center for Population and Development Studies,
Harvard School of Public Health, Boston, MA, USA

P. Vavken
Orthopedics, Harvard Medical School, Children's Hospital
Boston, Boston, MA, USA

Introduction

The Achilles tendon is the strongest tendon of the human body and has to withstand forces of up to 3,800 N [18]. The treatment of Achilles tendon ruptures should not only restore Achilles tendon length but the original strength of the whole muscle–tendon unit (MTU) [19, 35]. Force and

subjective strength are included in all clinical outcome scores such as the ATRS [28], the Hannover score [39] and the American Orthopaedic Foot and Ankle Society hind foot score [13] emphasizing the importance of strength recovery. [3, 7, 9, 10, 25, 36, 40]

A meta-analysis in 2005 stated that, for athletes, surgical treatment is generally preferred for Achilles tendon rupture [11, 12, 24, 32]. Other authors have focused their research on comparative studies of isokinetic or isometric peak plantar flexion torque (PPFT) [17, 26, 27]. Plantar pressure distribution (PPD) is an easy-to-measure examination that has not yet been used in outcome studies after Achilles tendon rupture, except for one case report [1]. Until now, these biomechanical measures have not been correlated to clinical scores and only to a small extent to radiological parameters.

The primary objective of this study was to systematically assess PPFT and push-off force (POFF) across the three mainstream treatment groups: open repair, percutaneous repair and non-surgical treatment at a minimum follow-up of 3 years. A second objective of this study was to test for correlation with calf muscle volume (MV), cross-sectional area and clinical outcomes, including subgroup analyses by type of treatment.

It was hypothesized that isokinetic PPFT and POFF in PPD analysis would be higher in the open surgery group due to better approximation of the tendon ends. It was also hypothesized that isokinetic torque per cubic centimetre

muscle would not be significantly different between treatment groups.

Materials and methods

This study was designed as a retrospective assessor-blinded, multi-centre trial (Fig. 1). Fifty-two patients (11 F, 41 M) were recruited from three orthopaedic centres in Switzerland (University Hospital Basel, Cantonal Hospital Liestal and Cantonal Hospital Fribourg). Demographic data can be seen in Table 1.

Patients who had unilateral Achilles tendon rupture were contacted a minimum of 3 years after the injury, mean time to contact was 7.5 years. Inclusion criteria were: 20–65 years of age, a healthy contralateral leg with physiological, clinically determined, alignment of the knee, foot and ankle, no trauma to the healthy leg, no neuromuscular impairments including muscle dystrophies, no other post-traumatic injuries or osteoarthritis of the knee, foot or ankle of the treated leg.

Exclusion criteria were: re-rupture or re-operation of the Achilles tendon, surgical site infection, neuromuscular diseases including muscle dystrophies, ankle valgus of more than 15° or ankle varus of more than 5°, other known pathologies of the non-treated leg, general MRI exclusion criteria (e.g. pacemaker, other metal not qualifying for an

Fig. 1 Study design. This flow chart depicts patient acquisition at the three hospitals, the number of exclusions as well as the pathway of examinations and analyses. *UHBS* University Hospital Basel, Switzerland, *KSLI* Cantonal Hospital Liestal, Switzerland, *HFR* Cantonal Hospital Fribourg, Switzerland

MRI, tattoos and claustrophobia) and a body mass index (BMI) of $>40 \text{ kg/m}^2$. All non-surgically treated patients were recruited from one study centre (Cantonal Hospital Fribourg) and all surgically treated patients were recruited from the two other study centres.

Post-operative regimens for surgically treated groups were identical in all study centres. Non-surgically treated patients were treated with early functional rehabilitation in a stability boot and a night splint. During recovery, all groups were allowed partial weight bearing for 2 weeks in 30° of plantar flexion. In weeks three and four patients were progressed to full weight bearing with 20° of plantar flexion and at week five and six patients were reduced to a 10° plantar flexing heel pad. After that plantigrade weight bearing in a stability boot for a total of 12 weeks was allowed.

Biomechanical assessment

Biomechanical data were obtained bilaterally, with the untreated leg serving as the normal, matched control of the treated leg. They were performed by a biomechanist with no prior relationship to the patient with the results analysed by a separate individual who was blinded to the treatment status of the patient. Peak ankle plantar flexion torque was tested on a HUMAC[®]/NORMTM (Computer Sports Medicine, Inc., Stoughton, MA, USA) at a speed of $30^\circ/\text{s}$ in concentric–concentric manner. The patient sat with the hip and knee fastened to the device to assure full knee extension. Following a warm-up period of 10 min on a cycling ergometer and three test runs to familiarize with the testing set-up, test runs were repeated three times per patient. The mean of these three runs was used for the analysis of PPFT and active ankle range of motion. Additionally, the angle at which the PPFT was reached was noted, with negative values depicting plantar flexion and positive values depicting dorsiflexion. The active range of motion during the isokinetic measurement was also recorded [6].

Plantar pressure distribution (PPD) analysis was performed on a FDM-T[®] (Zebris Medical GmbH, Isny, Germany) integrated into a treadmill ergo_run medical 8[®] (Daum electronic gmbh, Fürth, Germany) at a speed of 4 km/h and an acquisition frequency of 120 Hz. To prevent interference, each foot was tested with a separate force plate. For each foot, three non-measured test runs were performed for familiarization. Mean total peak POFF and separately mean peak forefoot POFF, step time, stride length, anterior-posterior and medio-lateral positioning of the centre-of-pressure (COP) line, length of COP-line and time change from heel to forefoot were averaged out of nine repeated measurements.

Radiological and clinical assessment

Following the method of Rosso et al. [33, 34], MV and cross-sectional area were recorded from MRI of both the treated and untreated legs. As previously published, the measurement accuracy was 0.1 cm. The test–retest correlation was found to be good (Cronbach's $\alpha = 0.84$). MVs were calculated for the gastrocnemius (medial and lateral) and soleus. The cross-sections used for measurements did not extend to the injury site to keep the analysis blinded.

Each patient was given ATRS [4], the Hannover score [5] and the AOFAS hind foot score [6] at the follow-up visit by an orthopaedic surgeon who was not their treating physician and who also measured the maximum calf circumference (MCC) with a tape measure. The ATRS score is a patient-completed outcome score with 10 questions on subjective functional outcomes. The Hannover score is a physician-completed outcome score in which force, range of motion (ROM) and proprioceptive measures are noted as well as subjective functional outcomes. The AOFAS hind foot score is a physician-completed and a more general hind foot score reflecting ROM, gait abnormality and ankle alignment and stability as well as subjective functional outcome measures. The main measure is pain, which makes up 40 % of the score.

IRB

All local institutions approved the human protocol for this investigation (Ethics Commission of Basel, Switzerland, IRB number 277/08). Investigations were conducted in conformity with ethical principles of research and informed consent for participation in the study was obtained.

Statistical analysis

Sample size was based on torque measurements in Newton-metres. Using data from the literature with 70 Nm (13 Nm SD) as a baseline outcome in the weakest group, an alpha of 5 % and a power of 80 %, a minimum total sample size of $n = 48$ patients in 3 groups was required (effect size = 0.47, critical $F = 3.2043$, $df = 2$).

Descriptive statistics, including mean with standard deviation and frequencies to describe the populations, were used, as appropriate.

A one-way analysis of variance (ANOVA) with Bonferroni post hoc analysis was used to compare the parameters noted in Tables 2 and 3. For all comparisons, R^2 values were calculated in addition to the ANOVA p values. For the comparison of the treated with untreated side, a paired t test was used. All reported tests were performed at the two-sided 5 % significance level with IBM SPSS Statistics Version 20.0[®], IBM Corporation, Armonk, New York.

Results

Isokinetic force measurements

The overall PPFT was 80.4 ± 29.7 Nm (mean $\pm$ standard deviation of the mean result for each patient) on the treated side and was not significantly different between the treatment groups. The untreated side showed a significantly higher PPFT of 92.1 ± 27.4 Nm and was on average 13 % higher compared to the treated side (80.4 ± 29.7 Nm, $p < 0.01$, Table 2). There was a significant gender difference for the treated side (59.2 ± 21.6 Nm in females and 86.1 ± 29.1 Nm in males, $p < 0.01$) and for the untreated side (70.3 ± 20.7 Nm in females and 97.9 ± 26.2 Nm in males, $p < 0.01$). The angle at which the maximum plantar flexion torque was reached was different on the treated side ($-4.5 \pm 7.2^\circ$, representing a mean plantar flexion of 4.5°) when compared to the untreated side ($-2.6 \pm 6.9^\circ$, $p = 0.04$), but did not show a significant difference in

treatment subgroup analysis. The active range of motion (ROM) during isokinetic force measurements of the treated side was not significantly different from the untreated side ($49.0 \pm 7.0^\circ$ vs. $49.9 \pm 7.1^\circ$).

Isokinetic force measurements with clinical and radiological correlations

Although statistically significant, clinical scores only showed a slight correlation with PPFT (Table 3). However, PPFT correlated significantly with MCC (BMI adjusted) (treated, $R^2 = 0.21$, $p < 0.01$; untreated, $R^2 = 0.31$, $p < 0.01$).

Peak plantar flexion torque (PPFT) correlated with MV on the treated side ($R^2 = 0.43$, $p < 0.01$), the same was found for the untreated side ($R^2 = 0.44$, $p < 0.01$). Males and females seem to have a similar torque per MV (0.113 ± 0.028 vs. 0.104 ± 0.031 Nm/cm³, $p = \text{n.s.}$) in analysis of maximum torque per cubic centimetre. The treated and untreated side did

Table 1 Patient demographics and clinical outcomes

	Tx group				ANOVA <i>p</i> value	<i>t</i> test vs. untreated <i>p</i> value
	Open <i>n</i> = 21	Percutaneous <i>n</i> = 16	Non-surgical <i>n</i> = 15	Total <i>n</i> = 52		
	Mean (SD)	Mean (SD)	Mean (SD)	Mean (SD)		
Follow-up [months]	97.5 (31)	83.4 (34)	90.1 (29)	91 (31)	n.s.	n.a.
Age at follow-up [years]	48.2 (11)	46.4 (7.1)	51.3 (6.9)	48.6 (8.7)	n.s.	n.a.
Age at injury [years]	40.3 (10)	39.6 (7.7)	44.2 (7.4)	41.2 (8.7)	n.s.	n.a.
Days off work	38 (23)	62 (67)	75 (175)	56 (100)	n.s.	n.a.
VSS						
No sports	1	0	2	3		n.a.
<1 h/week	3	3	1	7		n.a.
1–5 h/week	12	13	11	36		n.a.
>5 h/week	5	0	1	6		n.a.
Height [cm]	176 (9.2)	175 (8)	179 (9)	177 (8.8)	n.s.	n.a.
Weight [kg]	82.1 (14)	78.1 (14)	86.2 (9.8)	82.1 (13)	n.s.	n.a.
Scar						
Adherent	7	9	1	17	0.01*	n.a.
Palpation						
Mobile	14	7	14	35		n.a.
BMI [kg/m ²]	26.4 (4)	25.3 (3.2)	27.1 (4.3)	26.2 (3.9)	n.s.	n.a.
AOFAS score	97 (5.9)	93.2 (7.7)	93.4 (8.3)	94.8 (7.3)	n.s.	n.a.
ATRS score	90.5 (20)	88.4 (11)	90.6 (13)	89.9 (15)	n.s.	n.a.
Hannover score	86.7 (6.8)	80.2 (12)	79.1 (12)	82.5 (11)	n.s.	n.a.
Max. calf circumf. affected [cm]	38.1 (3.4)	37.7 (3.1)	37.7 (3.7)	37.9 (3.3)	n.s.	<0.01
Max. calf circumf. healthy [cm]	39.6 (3.1)	39.1 (2.6)	38.8 (3.4)	39.2 (3)	n.s.	n.a.
Max. calf circumf. (%)	0.96 (0)	0.96 (0)	0.97 (0)	0.97 (0)	n.s.	n.a.

Tx treatment, MV muscle volume, % percent of healthy side, SF36 short form 36, SD standard deviation, VSS valderrabano sports score, circumf. circumference, ATRS the Achilles tendon rupture score, AOFAS AOFAS hindfoot score, pat. patella., * Chi square, n.a. not applicable, n.s. not significant

Table 2 Biomechanical outcome parameters

	Treatment group						
	Open <i>n</i> = 21 Mean (SD)	Percutaneous <i>n</i> = 16 Mean (SD)	Non-surgical <i>n</i> = 15 Mean (SD)	Total <i>n</i> = 52 Mean (SD)	ANOVA <i>p</i> value	ANOVA vs. untreated <i>p</i> value	ANOVA <i>p</i> value
Open vs. percutaneous vs. non-surgical treatment							
Peak plantar flexion torque							
Treated [Nm]	88.7 (27.4)	76.1 (33.5)	73.3 (27.4)	80.4 (29.7)	n.s	<0.01	n.s.
Untreated [Nm]	97.4 (24.2)	91 (33.4)	85.9 (25)	92.1 (27.4)	n.s.	n.a.	n.s.
[fraction of untreated]	0.90 (0.11)	0.86 (0.26)	0.84 (0.19)	0.87 (0.19)	n.s.	n.a.	n.s.
At angle (treated) [degrees]	−6.2 (6.2)	−2.4 (9.2)	−4.2 (5.9)	−4.5 (7.2)	n.s.	0.04	n.s.
At angle (untreated) [degrees]	−3.9 (7.4)	−1.2 (8)	−2.1 (4.99)	−2.6 (6.9)	n.s	n.a.	n.s.
At angle [fraction of untreated]	0.89 (0.9)	1.11 (2.44)	0.81 (1.95)	0.95 (1.76)	n.s	n.a.	n.s.
Range of motion							
[Degrees]	43.4 (6.4)	47.8 (8.6)	49.8 (6.3)	49 (7)	n.s.	n.s.	n.s.
[Fraction of untreated]	0.96 (0.1)	0.97 (0.12)	1.04 (0.13)	0.99 (0.12)	n.s.	n.a.	0.04 ^a
Push-off force							
Treated [N]	807.4 (132)	764.9 (138)	785.2 (91.7)	787.9 (123)	n.s.	n.s.	n.s.
[Fraction of untreated]	0.99 (0.04)	1 (0.04)	0.97 (0.05)	0.99 (0.04)	n.s.	n.a.	0.03 ^a
Per <i>N</i> body weight	1.005 (0.08)	1.002 (0.1)	0.935 (0.11)	0.984 (0.1)	<i>n.s.</i>	<i>n.s</i>	0.02 ^a
Forefoot (treated) [N]	808.7 (130)	770.1 (132)	801.2 (88)	794.7 (119)	n.s.	n.s	n.s.
Step time [s]	0.54 (0.03)	0.53 (0.04)	0.53 (0.03)	0.53 (0.03)	n.s	n.s	n.s
Centre of pressure							
Line length [mm]	222.3 ^a (26.1)	213.3 (32.9)	184.2 ^a (46.9)	208.5 (38.1)	<0.01	n.s.	<0.01 ^a
Anterior/posterior position [mm]	143.5 (30.3)	131 (36.3)	151.7 (16.3)	142 (29.8)	n.s	n.a.	n.s.
Medial/lateral shift [mm]	−6.9 ^a (3.6)	−5.5 (4.3)	−3.3 ^a (5.5)	−5.4 (4.6)	n.s.	n.a.	0.03 ^a
Stride [cm]	121 (9)	116 (11.2)	115.3 (14.7)	117.8 (11.6)	n.s.	n.a.	n.s.
Length/body height	0.69 (0.04)	0.66 (0.04)	0.65 (0.09)	0.67 (0.06)	n.s.	n.a.	n.s.

SD standard deviation; %, percentage of untreated side, *n.a.* not applicable, *n.s.* not significant

^a Significance between the two marked groups

not statistically differ in torque per MV (0.114 ± 0.032 vs. 0.108 ± 0.024 Nm/cm³, $p = \text{n.s.}$). In treatment group analysis of the treated limb, open surgery outperformed non-surgical treatment (0.126 ± 0.025 vs. 0.099 ± 0.031 Nm/cm³, $p = 0.04$) and percutaneous treatment was in-between (0.113 ± 0.036 Nm/cm³).

Cross-sectional area seemed to be a good predictor of PPFT (treated, $R^2 = 0.35$, $p < 0.01$; untreated, $R^2 = 0.25$, $p < 0.01$). The ratio of PPFT and cross-sectional area revealed the same pattern as with PPFT per MV (treated, 1.90 ± 0.58 Nm/cm²; untreated, 2.05 ± 0.58 Nm/cm², $p = \text{n.s.}$) but was not significantly different in treatment subgroup analysis ($p = \text{n.s.}$). When surgery (open and percutaneous) was compared to non-surgical treatment, patients reached a higher PPFT per CSA in the intervention group (2.00 ± 0.58 vs. 1.64 ± 0.53 Nm/cm², $p = \text{n.s.}$).

Peak plantar flexion torque (PPFT) did not correlate with fatty atrophy (Table 3).

Plantar pressure assessment

The overall POFF for the treated leg was 787.9 ± 123.0 N and was not statistically different among the treatment groups or when the treated and untreated side were compared (Table 2). However, there was a notable difference when gender was compared with 682.3 ± 120.2 N in females and 816.3 ± 108.6 N ($p < 0.01$) in males, even with weight adjustment ($R^2 = 0.18$, $p < 0.01$).

Plantar pressure assessment with clinical and radiological correlations

Push-off force (POFF) correlated significantly with MCC (BMI adjusted) (treated, $R^2 = 0.29$, $p < 0.01$; untreated, $R^2 = 0.38$, $p < 0.01$). Nevertheless, clinical scores did not correlate with POFF of the treated side (ATRS,

Table 3 Predictors for peak plantar flexion torque and push-off force

	Peak plantar flexion torque		Push-off force (POFF)	
	R^2	p value	R^2	p value
ATRS	0.11 ^a	0.02	0.001	n.s.
Hannover score	0.16 ^a	<0.01	0.05	n.s.
AOFAS	0.03	n.s.	0.03	n.s.
Maximum calf circumference				
Treated	0.21 ^a	<0.01	0.29 ^{a, b}	<0.01
Untreated	0.31 ^a	<0.01	0.38 ^{a, b}	<0.01
Muscle volume				
Treated	0.43 ^a	<0.01	0.47 ^a	<0.01
Untreated	0.44 ^a	<0.01	0.40 ^a	<0.01
Cross-sectional area				
Treated	0.35 ^a	<0.01	0.47 ^a	<0.01
Untreated	0.25 ^a	<0.01	0.38 ^a	<0.01
Fatty atrophy				
Treated	0.008	n.s.	0.08 ^a	0.04
Push-off force				
Treated	0.31 ^a	<0.01	n.a.	
Untreated	0.30 ^a	<0.01	n.a.	

Depicted are R^2 values

n.a. Not applicable, ATRS the Achilles tendon rupture score, AOFAS American Orthopaedic Foot and Ankle Society Hindfoot score, n.s. not significant

^a Significant; ^b BMI adjusted

$R^2 = 0.001$, $p = \text{n.s.}$; AOFAS, $R^2 = 0.03$, $p = \text{n.s.}$; Hannover, $R^2 = 0.05$, $p = \text{n.s.}$.

Push-off force (POFF) was calculated per kilograms body weight [Newtons, factor 9.81 N/kg]. Mean POFF was 98.4 ± 9.7 % of the body weight on the treated side (untreated, 99.5 ± 9.4 %). There was no significant effect of treatment in subgroup analysis, however, when the open and percutaneous groups were combined into a surgical treatment group the surgical treatments showed a higher relative POFF per body weight on the treated side when compared to non-surgical treatment (surgery, 100.4 ± 8.5 %; non-surgical, 93.5 ± 10.9 %, $p = 0.02$, Table 2).

There is a correlation between POFF and MV, with an R^2 of 0.47 ($p < 0.01$) on the treated side and an R^2 of 0.40 on the untreated side ($p < 0.01$). Similar to MV, cross-sectional area (CSA) was a strong predictor of POFF (treated, $R^2 = 0.47$, $p < 0.01$; untreated, $R^2 = 0.38$, $p < 0.01$). Fatty atrophy only showed a weak correlation with POFF (treated, $R^2 = 0.08$, $p = 0.04$, Table 3).

When looking at other PPD parameters of the treated side (step time, stride length, length of the COP-line, anterior-posterior and medio-lateral position of the COP-line and POFF of the forefoot alone) only the length of the

COP-line differed significantly when compared to the untreated side (Table 2). The COP-line length was longer in the open surgery group (222.3 ± 26.1 mm) compared to the non-surgical group (184.2 ± 46.9 mm, $p < 0.01$). The percutaneous group (213.3 ± 32.9 mm) was not significantly different from the open or non-surgical treatment. We also found a significant difference in medio-lateral shift with values of -6.3 ± 3.9 in the surgical group and -3.3 ± 5.5 in the non-surgical group ($p = 0.03$; negative values represent a shift from medial to lateral).

Push-off force (POFF) seemed to be predictive of PPFT with a correlation of $R^2 = 0.31$ ($p < 0.01$, Table 3).

Discussion

In this study, we analysed biomechanical outcomes such as PPFT, POFF and MV, and compared these and clinical scores between the three mainstream treatment options for Achilles tendon rupture. No matter of which treatment was chosen, loss of function is commonly seen after Achilles tendon rupture [8, 31] and there remains dispute as to which treatment method results in the best functional and biomechanical outcomes [2–5, 7, 9, 10, 15, 21, 25, 30, 34, 36, 37, 40]. The most important findings of this study were that after 7.5 years of follow-up the relative POFF values regarding side comparison as well as relative to the body weight, surgical treatment outperformed non-surgical treatment. Range of motion as an indicator for Achilles tendon overlengthening was higher in the non-surgical group. Non-surgical treatment showed a shorter COP-line when compared to each of the surgical groups as well as when it was compared to the surgical group (open and percutaneous together).

Difference between the treated and untreated limb

When comparing the treated and untreated leg, Leppilahti et al. [17] studied 85 patients treated with open surgery and found a significant reduction in isokinetic plantar flexion torque measurements of the treated leg at different angular accelerations including $30^\circ/\text{s}$ (mean follow-up, 3.1 years). Our results showed a similar difference between the treated and untreated leg after several years of follow-up and are supported by other studies [3, 7, 9, 10, 25, 36, 40] (Table 2). Other studies [2, 4, 5, 21, 37] did not find a difference in isokinetic measurements between the injured and uninjured leg, though their measured values were in the same range as our measurements. The differences between these groups of studies can be explained by looking at the methods. The studies that found a difference compared surgical to non-surgical treatment, while the studies comparing surgical methods did not find a

difference. Similarly, most of our results did not show a difference between the surgical options, but did show a difference between surgical and non-surgical options.

Peak plantar flexion torque (PPFT) was found to be different between the treated and the untreated leg in line with one study having reported significant decrease after 2 years of follow-up [23]. A recent study by Olsson et al. [29] showed major functional deficits after a 2-year follow-up. This statement can be verified for our 7.5 years mean follow-up as well. In this study, the angle at which the PPFT reached was 1.9° or 0.06 s (at $30^\circ/\text{s}$) later on the treated side. This finding shows that the foot is more plantarflexed and the treated leg needs more time to produce PPFT, which might be due to a reduced force coupling between the muscle and bone with compliant tendon as seen with PPFT per cubic centimetre (discussed below). There are no comparative studies in the literature on this. The ratio of PPFT to MV was comparable in males and females and was similar on the treated and untreated leg showing that the muscle force generated per volume might be maintained. Since MV remains higher on the untreated side, the absolute PPFT remained higher on the untreated leg. The ratio of PPFT/MV might be a more sensitive parameter than either alone when evaluating strength measurements, as previously shown for PPFT per cross-sectional area [17].

Difference between treatment groups

Häggmark, Metz and Willits compared open and non-surgical treatment groups and did not find a significant difference in isokinetic torque measurements between the treatment groups, a result consistent with our findings with regard to the relative measurements at $60^\circ/\text{s}$ (treated vs. untreated) [8, 22, 41]. As patients with a high muscle mass have higher PPFT's [38], we looked at PPFT per cubic centimetre MV. In this measurement, open surgery had a higher value [Nm/cm^3] compared to non-surgical treatment, which might be due to a better force coupling between the two former ruptured tendon parts in open surgery resulting in a less compliant tendon. Until now, the ratio Nm/cm^3 has not been compared between treatment groups, it has only been compared between the treated and untreated side only with cross-sectional area [17]. The previously published values of PPFT per cross-sectional area and the values reported in this study were in the same range of about $2 \text{ Nm}/\text{cm}^2$ [17, 22, 41]. Similarly, a recent study did not find a significant difference between surgical and non-surgical treatment by means of concentric heel-rise tests, jump tests and muscular endurance [30].

In PPD measurements, multiple differences were found, similar to other studies [17]. The COP-line was significantly longer in the open surgery group when compared to the non-surgical group showing an increased functional use

of the foot with a later push-off and thus better use of the forefoot. The length of the COP was not found to be different in a study comparing healthy subjects to percutaneously operated patients after a mean follow-up of 2 years [23]. POFF was calculated per body weight as a main co-variable. Relative push-off force (POFF %, Table 2) and POFF per Newton body weight were both higher in the surgery group (open and percutaneous). To our knowledge, the important ratios of PPFT per MV and POFF per body weight have not been looked at in the previously published Achilles tendon rupture literature. We also found a significant medial to lateral shift. The surgical group seemed to have a more lateral weight bearing than the non-surgical group, which might be due to a better working Achilles tendon, a foot inverter [14] and consequently increasing the load of the lateral foot [1]. Consistent with the results reported by Chan et al. [4], no significant difference in stride length between the treatment groups was found.

Interestingly, the relative range of motion of the ankle joint (dorsal extension and plantar flexion) was different between the groups (Table 2) with a significantly higher ratio in the non-surgically treated group. We believe that this might be due to an overlength of the Achilles tendon with a longer tendon in the non-surgically treated group, which was shown in a previous publication [33].

As expected, male patients had higher PPFT and POFF values compared to female patients, but when analysed by looking at torque per cubic centimetre the gender difference disappeared. Previously torque has been normalized with body mass and not MV [16].

A positive correlation between PPFT and both MV and cross-sectional area as found in other studies was shown [17]. Cross-sectional area was also found to be a main determinant of muscle strength in isometric measurements [20]. Peak POFF was correlated with MV and cross-sectional area as well. This was not surprising, as PPFT and POFF correlate ($R^2 = 0.31$, $p < 0.01$). As MV and cross-sectional area correlated with MCC, the positive finding of correlations of MCC with PPFT and POFF was expected. Neither PPFT nor POFF correlated clearly with clinical scores such as the ATRS, the Hannover score or the AO-FAS Hind foot score. No significant correlation between fatty atrophy and PPFT or POFF was found.

The limitations of the study are as follows. This study was performed as a retrospective study, which could introduce some bias, but this disadvantage might be balanced by the length of follow-up that would otherwise be very difficult to achieve in a timely manner in a prospective study. All of the non-surgical patients were recruited from a single centre, so differences in this group could be due to population differences. Indications for surgical therapy might differ between centres and surgical techniques vary depending on the surgeon as well as the implementation of

the rehabilitation protocol, a common limitation in multi-centre studies. In addition, it has to be pointed out that complications such as re-rupture or surgical site infection were exclusion criteria and thus not analysed.

Nevertheless, this study has several strengths. The biomechanist evaluated the biomechanical measures without prior knowledge as to which was the treated or untreated leg. The orthopaedic surgeon who scored the clinical measurements and managed the database was not the treating physician of any of the patients. PPD measurements were performed on a treadmill at 4 km/h. In this way, the patient did not concentrate on reaching the pressure platform, which might possibly lead to an increased heel strike force.

For the clinician, this study shows that clinical outcomes only weakly correlate with biomechanical outcome parameters and that clinically measured MCC can be an easy-to-measure parameter reflecting the amount of PPFT a patient can exert. This parameter can be used for patients post-operatively after Achilles tendon rupture repair as well as healthy patients.

Conclusions

Clinical scores (AOFAS, ATRS, Hannover) did not reflect biomechanical outcomes. Clinically measured MCC seemed to be a good predictor of PPFT. The POFF and PPFT were correlated, but these measurements should still be used and cannot be replaced by one another. Some measures implied better biomechanical outcomes after open and percutaneous surgical treatment.

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Conflict of interest Each author certifies that he or she has no commercial associations that might pose a conflict of interest in connection with the submitted article.

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