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Normative ultrasound values for Achilles tendon thickness in the general population and patients with Achilles tendinopathy: A large international cross-sectional study

Tjerk S. O. Sleeswijk Visser[1] | **Seth O'Neill**[2] | **Joost W. Colaris**[1] | **Denise Eygendaal**[1] | **Robert-Jan de Vos**[1]

[1]Department of Orthopedics and Sports Medicine, Erasmus MC University Medical Centre, Rotterdam, The Netherlands

[2]Department of Life Sciences, School of Allied Health, University of Leicester, Leicester, UK

Correspondence
Tjerk S. O. Sleeswijk Visser, Department of Orthopedics and Sports Medicine, Erasmus MC University Medical Centre, Dr. Molewaterplein 40, 3015 GD Rotterdam, The Netherlands.
Email: t.sleeswijkvisser@erasmusmc.nl

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Abstract

The objective of the study was to obtain adjusted ultrasonographic reference values of the Achilles tendon thickness (maximum anterior–posterior distance) in adults without (previous) Achilles tendinopathy (AT) and to compare these reference values with AT patients. Six hundred participants were consecutively included, comprising 500 asymptomatic individuals and 100 patients with clinically diagnosed chronic AT. The maximum tendon thickness was assessed using Ultrasound Tissue Characterization. A multiple quantile regression model was developed, incorporating covariates (personal characteristics) that were found to have a significant impact on the maximum anterior–posterior distance of the Achilles tendon. A 95% reference interval (RI) was derived (50th, 2.5th-97.5th percentile). In asymptomatic participants median (95% RI) tendon thickness was 4.9 (3.8–6.9) mm for the midportion region and 3.7 (2.8–4.8) mm for the insertional region. Age, height, body mass index, and sex had a significant correlation with maximum tendon thickness. Median tendon thickness for the midportion region was calculated with the normative equation −2.1 + AGE ×0.021 + HEIGHT ×0.032+ BMI ×0.028 + SEX ×0.05. For the insertional region, the normative equation was −0.34 + AGE ×0.010+ HEIGHT ×0.018 + BMI ×0.022 + SEX × −0.05. In the equations, SEX is defined as 0 for males and 1 for females. Mean (95% CI) difference in tendon thickness compared to AT patients was 2.7 mm (2.3–3.2, $p < 0.001$) for the midportion and 1.4 mm (1.1–1.7, $p < 0.001$) for the insertional region. Compared to the asymptomatic population 73/100 (73%) AT patients exhibited increased tendon thickening, with values exceeding the 95% RI. This study presents novel reference values for the thickness of midportion and insertional region of the Achilles tendon, which were adjusted for personal characteristics. Our novel web-based openly accessible calculator for determining

normative Achilles tendon thickness (www.achillestendontool.com) will be a useful resource in the diagnostic process.

Trial registration number: This trial is registered in the Netherlands Trial Register (NL9010).

KEYWORDS

imaging, reference values, tendon geometry, ultrasound tissue characterization

1 | INTRODUCTION

Achilles tendinopathy (AT) is the preferred term for local tendon pain related to mechanical loading.[1] It is frequently occurring (2–3/1000 individuals),[2] longstanding (20%–30% persisting symptoms at 10-year follow-up),[3,4] has a large impact on quality of life and is associated with substantial costs (840€/patient/year in a western European country).[5]

Ultrasound is the preferred method for imaging of the Achilles tendon according to the current guidelines.[6,7] In the longitudinal plane the Achilles tendon exhibits a pattern of parallel fibrillar lines, while in the transverse plane, it presents as a round-to-ovoid echogenic shape.[6] AT is ultrasonographically characterized by tendon thickening in the anterior–posterior direction and a decreased tendon structure.[8,9]

Imaging could aid in establishing the diagnosis of AT.[10] Currently, maximum Achilles tendon thickness is estimated at approximately 6 to 7 mm based on clinical experience and cross-sectional studies.[6,8,11–15] An important knowledge gap with imaging is that current normative values for Achilles tendon thickness may not be representative of the general population and no studies differentiated between the midportion and insertional region of the tendon.[14–16] Previous studies also showed a considerable deviation surrounding the normative values for Achilles tendon thickness.[14] It is likely that tendon thickness is influenced by personal characteristics. Obtaining reference values for Achilles tendon thickness and addressing important personal characteristics will aid clinicians in differentiating between AT and 'normal' morphological changes, which will facilitate personalized healthcare.

The primary aim of this study aim is to obtain ultrasonographic reference values of the Achilles tendon thickness (maximum anterior–posterior distance) in adults without (previous) Achilles tendinopathy. The secondary aim is to compare these reference values with tendon thickness in patients with clinically diagnosed AT.

2 | METHODS

2.1 | Study design

The study was designed at the Erasmus MC University Medical Centre (Rotterdam, the Netherlands) in collaboration with the University of Leicester (Leicester, United Kingdom) and conducted at the outpatient departments of these universities from October 2020 to July 2023. The study was temporarily halted between November 2020 and May 2022 because of COVID-19 related restrictions. These restrictions also forced us to adjust the number of participants to 500, which is a decrease by 100 participants compared to the pre-defined protocol. The local Medical Ethics Committee (Southwest-Holland, the Netherlands) approved the study protocol (MEC-2020-0585). The trial was registered before commencement (Netherlands Trial Register, NL9010). We adhered to the Strengthening the Reporting of Observational Studies in Epidemiology (STROBE) guidelines for the reporting of observational studies.[17]

2.2 | Participants and procedures

2.2.1 | Asymptomatic population

A study announcement was made through informing potential participants via social media platforms (Twitter, Facebook, LinkedIn and internal websites). If participants expressed interest to participate and passed an online screening, an appointment with a researcher was planned to further assess eligibility and perform measurements in case of inclusion. The inclusion criteria were: (1) Age ≥ 18 years, (2) no current Achilles tendon pain or stiffness, (3) no localized fusiform thickening of the Achilles tendon on palpation, (4) no history of pain or stiffness in the Achilles tendon region and (5) full score on the adapted Victorian Institute of Sports Assessment-Achilles (VISA-A) questionnaire (question 1–question 5).[18,19] The exclusion criteria were: (1) Achilles tendon or

ankle surgery in the past, (2) known systemic inflammatory disorders or internal diseases that can cause Achilles tendon abnormalities (e.g. Spondylarthropathy, Psoriatic Arthritis or Familial Hypercholesterolaemia) and (3) recent (past 12 months) lower-limb injury requiring immobilization. Additionally, participants who experienced technical malfunctions with the UTC, such as an empty battery or software errors during scanning, were asked to schedule a new appointment. If rescheduling was not feasible for the participant, they were excluded to ensure the reliability of our data collection.

If the inclusion criteria were met, participants were asked to sign the written informed consent form. Subsequently, participants completed a more extensive questionnaire with collection of demographic data (age, sex, height, weight and body mass index [BMI]), past medical history (presence of comorbidities), medication use (including past or current use of fluoroquinolones and statins), smoking and current and past physical activities. A 6-point Likert scale[20] and the Sports Activity Rating Scale[21] were used to rate physical activity. Thereafter a short physical examination was performed, assessing the amount of localized pain on Achilles tendon palpation (using a 0–10 Visual Analogue Scale; VAS) and localized fusiform tendon thickening using the Arc sign (positive when the area of swelling identified with palpation moves with ankle range of motion).[22] Subsequently, the UTC procedure was carried out on both Achilles tendons when the participant was eligible.

2.2.2 | Achilles tendinopathy patients

All adult patients who visited the outpatient Department of Orthopedics and Sports Medicine of the Erasmus MC University Medical Centre with a clinical diagnosis of AT were eligible to participate. Patients were included if: (1) the clinical diagnosis of AT was established by the clinician, (2) informed consent was provided, (3) the baseline questionnaire was completed, and (4) the ultrasound tissue characterization (UTC) procedure was performed.

Patients completed a digital questionnaire prior to their appointment at the outpatient department. The questionnaire included information on demographics, lifestyle habits, comorbidities, work, injury characteristics, and physical activity level. The VISA-A questionnaire was also completed.[18] A single senior sports physician (RJDV) performed complete history taking and physical examination, which included assessing pain on tendon palpation and the presence/absence of tendon thickening. The clinical diagnosis was made based on history and physical examination. The clinician established the clinical diagnosis of AT if the pain was (1) located to the Achilles tendon region, (2) associated with Achilles tendon-loading activities, and (3) provoked on Achilles tendon palpation.[1,7,10,22] If the pain was localized at the level of the posterior calcaneus, insertional Achilles tendinopathy was diagnosed and if the pain was localized above the superior border of the posterior calcaneus, midportion Achilles tendinopathy was diagnosed. Hereafter, the UTC procedure was carried out on the symptomatic side. In case of bilateral symptoms, the side with the most severe complaints was scanned.

2.3 | Outcome measures

2.3.1 | Ultrasound tissue characterization

Primary outcome measure was the maximum anterior–posterior (AP) distance of the Achilles tendon in transversal view (also referred to as thickness) using UTC. Achilles tendon thickness can be depicted with UTC.[8,11,23] The UTC is a customized tracking and ultrasonographic data-collection device that allows for objective, standardized measurements, which can be translated to conventional ultrasound.[8] The UTC Imaging version 2020 (UTC Imaging, Stein, The Netherlands), consisting of conventional ultrasound equipment (multi-frequency 5–16 MHz linear-array transducer) and a tracking device, was used. At each site, one single trained researcher (TSV and SO) performed all UTC scans. Participants were positioned prone on an examination table with a maximum tolerable dorsiflexion angle of the ankle.[8] The transducer was placed in a transverse position to the Achilles tendon and moved automatically from proximal to distal over a distance of 12 cm.[24] Images were stored using a specific code and analysis of the images was performed in a subsequent stage of the research project. Previous studies have described the UTC procedure in more detail.[8,11,12,23]

Image analysis of all UTC scans was performed by one trained researcher (TSV). This researcher was blinded to patient characteristics while performing the analyses. The maximum anterior–posterior distance was measured with the UTC software. In the longitudinal plane (sagittal view), we screened for the area of maximum thickness in the midportion and insertional region of the tendon (Figure 1). Hereafter this area was evaluated in the transverse plane and in this view, we estimated the maximum thickness and measured it. The insertional region was defined as the area from the lowest Achilles tendon insertion on the calcaneus to the upper border of the posterior calcaneus. The midportion region was defined as the area proximal to the upper border of the posterior calcaneus.

The inter- and intra-rater reliability for AP-measurements have been shown to be excellent for AT

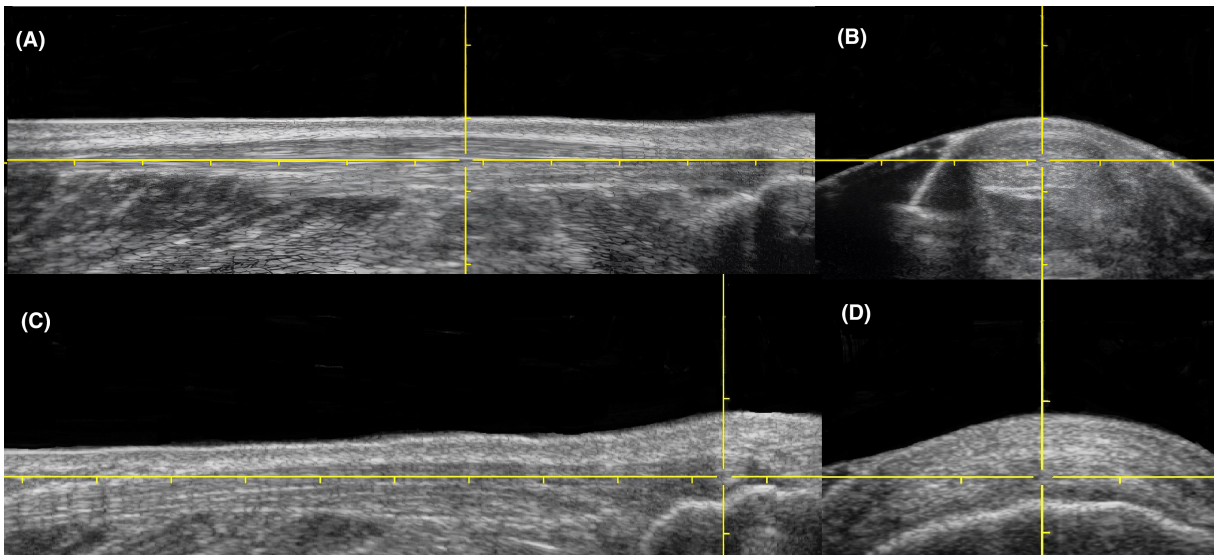

FIGURE 1 UTC image of the Achilles tendon. In the longitudinal plane (A, C), the thickest part of both the midportion and insertional region of the tendon were estimated. Subsequently, those regions were assessed in the transversal plane (B, D). (A, B) midportion region of the Achilles tendon. (C, D) insertional region of the Achilles tendon.

patients (intra-class correlation coefficient [ICC] 0.93 and 0.95 respectively) as well as for asymptomatic participants (ICC 0.91 and 0.94).[25]

2.4 | Statistical analysis

To establish normative equations for maximum AP distance of Achilles tendon thickness, the data from 500 subjects were inspected using scatter- and boxplots to identify outliers. Descriptive statistics were used for presentation of personal characteristics. Quantile regressions were used for analysis, given the expected skewed nature of the data and the aim to establish normative values. Quantile regression allows for estimations of medians and does not make distributional assumptions.[26] Potential differences in tendon thickness between the right and left leg were analyzed using a Wilcoxon signed-rank test (in the case of non-normal distribution) for the midportion and insertion region. When no statistically significant differences were observed, data is presented as the mean tendon thickness for the midportion and insertional region. Bivariate models were constructed for each covariate (age, sex, height, weight, BMI, activity level, leg dominance, smoking, alcohol consumption and presence of comorbidities) for the midportion and insertion region separately on both sides. Hereafter, a multiple quantile regression model was built using the covariates that significantly influenced the maximum anterior–posterior distance of the midportion and insertion region. Participants with missing data on any of the covariates that significantly influenced maximum AP-distance were omitted from the multiple regression analysis. The median (50.0th), lower (2.5th), and upper (97.5th) percentile values of the regression model's results were extracted to present tendon thickness as median with a 95% reference interval (RI) encompassing the 50th percentile within the range of the 2.5th to 97.5th percentiles. To effectively assess the influence of each covariate on tendon thickness, the 95% confidence intervals (CI) were also extracted. This allows the estimation of the impact of each covariate on tendon thickness for both the midportion and insertional region. For the secondary objective, we aimed to include 100 AT patients. We compared the tendon thickness between AT patients and asymptomatic individuals for the midportion and insertional region using a general linear model while adjusting for the variables that significantly differed between both groups. We adhered to the CHecklist for statistical Assessment of Medical Papers (CHAMP) statement for the statistical analysis and presentation of results.[27] IBM SPSS Statistics (version 28.0.1.0) were used.

3 | RESULTS

A total of 684 persons were screened for eligibility and finally 500 asymptomatic participants and 100 AT patients, with complete data for the primary outcome measure of tendon thickness, were included. A flowchart and reasons for exclusions is presented in Figure 2. The main participants' characteristics are depicted in Table 1. Among the participants, 55% were female, while 8 participants did not want to disclose their sex. Patients with AT had a median [interquartile range (IQR)] symptom duration

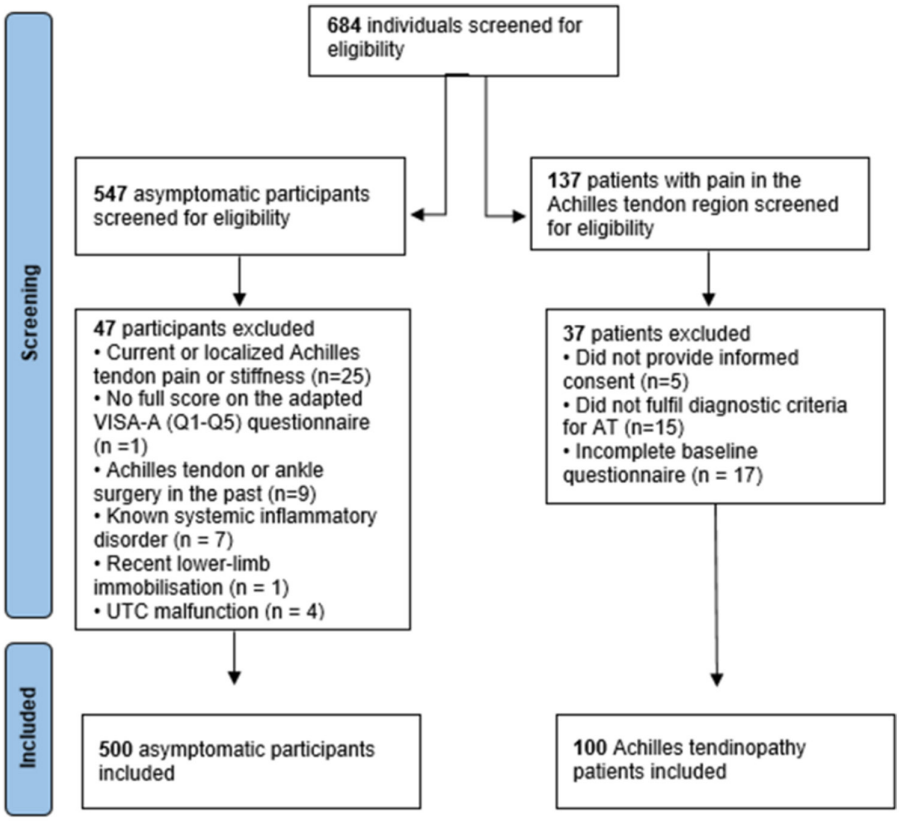

FIGURE 2 Flowchart of the study.

TABLE 1 Participant characteristics.

	Total Group ($n=600$)	Achilles tendinopathy patients ($n=100$)	Asymptomatic participants ($n=500$)	Mean difference (95% CI, p-Value)
Age (years)	34 [23–53]	48.0 (12.8)	30 [22–50]	11.8 (8.4–15.2, $p<0.001$)
Height (cm)	174.9 (9.5)	178.6 (8.8)	174.2 (9.5)	4.4 (2.4–6.4, $p<0.001$)
BMI (kg/m^2)	23.6 [21.8–26.2]	26.1 (4.5)	23.3 [21.7–25.6]	2.1 (1.3–2.9, $p<0.001$)
Sex (female/male/undisclosed, n)	317/275/8	43/57	274/218/8	$p=0.020$
Physical activity level (PAL; 1–6)	5 [4–6]	3 [3–4]	5 [4–6]	$p<0.001$
Symptom duration (weeks)	—	108 [50–260]	—	—
VISA-A score (0–100)	—	48.0 (17.5)	98.9 (3.3)	50.9 (49.3–52.6, $p<0.001$)
Tendon thickness (mm; midportion)	—	9.2 (2.5)[a]	4.9 [3.8–6.9][b]	2.7 (2.3–3.2, $p<0.001$)[c]
Tendon thickness (mm; insertion)	—	5.7 (1.4)[a]	3.7 [2.8–4.8][b]	1.4 (1.1–1.7, $p<0.001$)[c]
Medication use (yes/no)	181/419	53/47	128/372	—
Smoking (current/past/never)	33/67/500	5/34/61	28/33/439	—
Presence of co-morbidities (yes/no)[d]	71/529	19/81	52/448	—

Note: Values are means with standard deviation (SD) or medians with interquartile ranges [IQR] unless otherwise described.

Abbreviations: AT, Achilles tendinopathy; BMI, Body mass index (kg/m^2); PAL, Physical Activity Likert Scale; VISA-A, Victorian Institute of Sports Assessment-Achilles; 1–6*, 1 = Hardly any physical activity, 2 = Mostly sitting, sometimes walk, easy tasks/play, 3 = Light physical activity for about 2–4 times a week (e.g., fishing, talking, dancing), 4 = Moderate exercise 1–2 h a week (jogging, swimming, gymnastics), 5 = Moderate exercise at least 3 h a week (jogging, swimming, gymnastics), 6 = Hard or very hard exercise regularly and several times a week during which the physical exercise is great (jogging, rugby, football).

[a]Midportion thickness included 64 patients with midportion AT. Insertional thickness included 34 patients with insertional AT. Two patients had a combination of midportion and insertional AT.

[b]95% reference interval.

[c]Adjusted for age, height, sex, BMI and physical activity level.

[d]Comorbidities include diabetes mellitus, hypertension, hypercholesterolemia, heart-vessel disease and thyroid disease.

of 108 [50–260] weeks. Midportion AT was reported in 64 patients and 34 patients had insertional tendinopathy (2 patients had a combination of midportion and insertional AT). Bilateral symptoms were present in 36/100 (36%) of the AT patients.

3.1 | Normative values for Achilles tendon thickness

There was no significant difference between the left and right leg for tendon thickness of the midportion region (5.06 vs 5.05 mm, $p=0.728$) and the insertional region (3.72 vs. 3.71 mm, $p=0.967$). Bivariate analyses revealed that age ($r=0.46$, $p<0.001$ and $r=0.33$, $p<0.001$), height ($r=0.31$, $p<0.001$ and $r=0.34$, $p<0.001$), BMI ($r=0.17$, $p<0.001$ and $r=0.22$, $p<0.001$) and sex ($r=0.15$, $p<0.001$ and $r=0.25$, $p<0.001$) had a correlation with maximum tendon thickness of the midportion and insertional region respectively. Leg dominance did not influence tendon thickness ($r=0.032$, $p=0.48$ for the midportion and $r=0.007$, $p=0.87$ for the insertion). The median (95% RI) AP thickness in asymptomatic individuals for the midportion region was 4.9 mm (3.8–6.9) and 3.7 mm (2.8–4.8) for the insertional region.

Age and height had the largest influence on tendon thickness, with older age and higher height being associated with increased values for tendon thickness (Table 2). In the bivariate analysis, male sex was found to be positively correlated with tendon thickness but this effect was not significant in the multiple quantile regression model (Table 2). The results of the multiple quantile regression model ($n=492$, $R^2=0.22$ for the midportion and $R^2=0.16$ for the insertion) with the relevant parameters is provided in Table 2. The data for the eight participants who opted not to disclose their sex were excluded from the multiple quantile regression analysis.

Estimates of normative median (95% RI) values for tendon thickness of the midportion and insertional region are presented in Table 3.

3.2 | Difference between asymptomatic individuals and patients with Achilles tendinopathy

Patients with AT were on average older, taller, had a higher BMI and a lower physical activity level than the asymptomatic participants (Table 1). Maximum tendon thickness as measured with UTC is also displayed in Table 1. The mean difference (95% CI) in tendon thickness, adjusted for age, sex, height, BMI and physical activity level, between the asymptomatic population and AT patients was

TABLE 2 Estimates (95% CI, *p*-value) of the effect of the parameters on maximum Achilles tendon thickness derived from the multiple quantile regression analysis adjusted for age, height (cm), BMI and sex.

Variable	Parameter estimated in the midportion region	Parameter estimated in the insertional region
Intercept	−2.1 (−3.7, −0.35)	−0.34 (−1.6, 0.9)
Age	0.021 (0.017, 0.025, $p=0.000$)	0.010 (0.007, 0.012, $p<0.001$)
Height	0.032 (0.023, 0.041, $p<0.001$)	0.018 (0.012, 0.025, $p<0.001$)
BMI	0.028 (0.010, 0.045, $p=0.003$)	0.022 (0.009, 0.036, $p=0.001$)
Sex	0.054 (−0.11, 0.22, $p=0.553$)	−0.050 (−0.18, 0.78, $p=0.446$)
Normative equation[a]	Intercept + age + height + BMI + sex	
Example A	Female, 23 years, 20 kg/m^2, 165 cm	
Example B	Male, 58 years, 28 kg/m^2, 186 cm	
Tendon thickness (midportion)[b]	−2.1 + 0.021 × (age) + 0.032 × (height) + 0.028 × (BMI) + 0.054 × (sex)	
A: 4.3 (3.1–5.5) mm	−2.1 + 0.021 × (23) + 0.032 × (165) + 0.028 × (20) + 0.054 × (1)	
B: 5.9 (4.6–7.9) mm	−2.1 + 0.021 × (58) + 0.032 × (186) + 0.028 × (28) + 0.054 × (0)	
Tendon thickness (insertion)[b]	−0.34 + 0.010 × (age) + 0.018 × (height) + 0.022 × (BMI) + 0.050 × (sex)	
A: 3.2 (2.7–4.1) mm	−0.34 + 0.010 × (23) + 0.018 × (165) + 0.022 × (20) − 0.050 × (1)	
B: 4.2 (3.3–5.6) mm	−0.34 + 0.010 × (58) + 0.018 × (186) + 0.022 × (28) − 0.050 × (0)	

Note: Examples on how to employ the normative equations based on two fictional patients are provided in the lower part of the table.

Abbreviation: BMI, Body mass index.

[a]Sex: male = 0, female = 1.

[b]Values are median (mm) with 95% RI (2.5th percentile, 97.5th percentile).

TABLE 3 Estimates of the normative median (50th), lower (2.5th) and upper (97.5th) percentile values (upper, lower) of Achilles tendon thickness for the midportion and insertional part of the tendon, presented by sex for each decade of life.

	Male		Female	
Age (years)	**Midportion**	**Insertion**	**Midportion**	**Insertion**
20	4.9 (4.1, 6.0)	3.7 (3.0, 4.8)	4.4 (3.1, 5.6)	3.3 (2.8, 4.2)
30	5.1 (4.2, 6.4)	3.8 (3.0, 4.9)	4.6 (3.2, 6.0)	3.4 (2.8, 4.4)
40	5.3 (4.4, 6.8)	3.9 (3.1, 5.1)	4.8 (3.3, 6.4)	3.5 (2.9, 4.5)
50	5.5 (4.5, 7.2)	4.0 (3.1, 5.2)	5.0 (3.5, 6.8)	3.6 (3.0, 4.7)
60	5.7 (4.6, 7.6)	4.1 (3.2, 5.4)	5.2 (3.6, 7.2)	3.7 (3.0, 4.8)
70	5.9 (4.7, 8.0)	4.2 (3.3, 5.6)	5.4 (3.7, 7.6)	3.8 (3.1, 5.0)
80	6.2 (4.8, 8.4)	4.3 (3.3, 5.7)	5.6 (3.8, 8.0)	3.9 (3.1, 5.2)

Note: Estimates are for individuals with a body mass index of 24.0 kg/m^2 and a height of 183 cm (males) or 170 cm (females).

2.7 mm (2.3–3.2, $p < 0.001$) for the midportion and 1.4 mm (1.1–1.7, $p < 0.001$) for the insertional region.

Using the normative equations for the median, lower (2.5th) and upper (97.5th) values of tendon thickness for each AT patient, we found that 73/100 patients (73%) had increased tendon thickening (a value larger than the 97.5th percentile).

4 | DISCUSSION

In this large international cross-sectional study, we demonstrated that Achilles tendon thickness is influenced by personal characteristics. We found that age and height had the largest influence on maximum anterior–posterior distance. The mean difference in tendon thickness between asymptomatic persons and patients with Achilles tendinopathy was 2.7 mm for the midportion region and 1.4 mm for the insertional region. The majority of the AT patients (73%) had an increased tendon thickening outside the 95% reference interval.

This study presents novel reference values for the thickness of the midportion and insertional region of the Achilles tendon, which have been lacking in the literature. Currently, maximum Achilles tendon thickness is estimated at 6 to 7 mm based on clinical experience and cross-sectional studies.[13–15] These studies have reported a considerable deviation surrounding the normative values for Achilles tendon thickness in selected (e.g. pre-dominantly military recruits or elite fencers)[13,14] or relatively small samples (ranging from 6 to a maximum of 100 individuals).[8,11,12] These studies reported different mean values of tendon thickness ranging from 4.2 to 7.1 mm, without adjusting for personal characteristics.[8,11–15] The relatively small and/or selected study populations in these studies may account for the variation in findings and no studies differentiated between the midportion and insertional region of the tendon, while these are considered separate clinical entities based on the current guidelines.[7,28]

The influence of personal characteristics on Achilles tendon thickness has been evaluated once in the past. A larger study ($n = 267$) by Koivunen-Niëmela et al. in 1995 evaluated the influence of personal characteristics on Achilles tendon thickness in an asymptomatic population. A large proportion of the population were military recruits who were predominantly male between the ages of 18–29.[14] This study found that there was a significant correlation between tendon thickness and age, height, and weight, with tendon thickness increasing from 5.9 mm in those aged 10–17 years to 6.7 mm in those aged >30 years.[14] These findings are consistent with those of the current study that is performed on a larger scale and without a clear selection, which also found that tendon thickness is largely influenced by age and height.

4.1 | Clinical implications

Imaging techniques have been found to aid in the diagnosis of Achilles tendinopathy, particularly in challenging cases where not all clinical diagnostic criteria are met.[7,10] It is, however, important to note that imaging may present a potential drawback, as findings suggestive for tendinopathy can be detected in 25% of asymptomatic Achilles tendons.[10,16] Additionally, our study shows that 27% of the patients with clinical diagnostic criteria for AT do not have increased Achilles tendon thickness outside the 95% reference interval. While abnormal imaging might increase the likelihood of AT, these findings challenge the use of imaging as gold standard for diagnosing AT.

Clinicians can benefit from having knowledge of reference values and parameters that impact on tendon thickness, which can help to distinguish between AT and normal morphological changes www.achillestendontool.com.

4.2 | Strengths and limitations

This study has several strengths. To our knowledge this is the largest cross-sectional study on this subject. We used strict methods, a pre-defined protocol and included an international cohort drawn from the general population which improves generalizability of the findings. Next to this, the outcomes of the quantile regression model are openly available, serving as a calculator for normative tendon thickness. The study also has limitations that must be acknowledged. First, only the maximum AP distance was used as an outcome measure in this study. While this is the most frequently used outcome measure when assessing Achilles tendon geometry, it does not fully capture the geometry of the tendon. Future research could focus on obtaining normative values for different measures of tendon geometry (e.g. cross-sectional area and volume) as well as for tendon structure. Second, we predefined fusiform Achilles tendon thickening as an exclusion criterion for asymptomatic participants. This might jeopardize generalizability, as there might be persons without (previous) Achilles tendon pain but a local thickened tendon. This might have overestimated the difference in ultrasonographic tendon thickness between asymptomatic and symptomatic individuals. We acknowledge this, but we feel that this choice was justified as one of the diagnostic criteria for AT is localized tendon thickening. Third, we used the UTC procedure to obtain ultrasonographic values for Achilles tendon thickness. It is questionable whether the results of this sophisticated procedure can be extrapolated to the procedures using conventional ultrasound in daily clinical practice. Nevertheless, we have recently showed a clear agreement (ICC 0.95) in obtained Achilles tendon thickness between the UTC procedure and conventional ultrasound procedure in the clinical setting.[25] Fourth, the methods used to assess the physical activity level of participants represent a limitation of our study as the specific questionnaires we used may not have fully captured the nuances of the participants' physical activity levels (e.g. intensity, frequency, and type of activity). Fifth, we did not evaluate the effects of race or ethnicity as we did not obtain these data.

5 | PERSPECTIVE

Achilles tendon thickness is influenced by personal characteristics with older age and higher height being associated with increased values for Achilles tendon thickness. The normative ultrasonographic values for tendon thickness derived from this study can help clinicians to differentiate between physiological morphological changes and features consistent with Achilles tendinopathy. The openly accessible web-based calculator for normative values of Achilles tendon thickness adjusted by personal characteristics can be accessed at www.achillestendontool.com and may help clinicians to distinguish between ultrasonographic features of Achilles tendinopathy and normal morphological changes.

AUTHOR CONTRIBUTIONS

TSV, RJDV, and SON designed the study. TSV, RJDV, JC, and SON performed data acquisition. TSV performed data analysis. All authors contributed to the interpretation of the data and drafted the manuscript. All authors gave their final approval to this version of the manuscript and agree to be accountable for all aspects of this work.

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CONFLICT OF INTEREST STATEMENT

The authors declare there is no conflict of interest.

DATA AVAILABILITY STATEMENT

Data are available upon reasonable request.

CONSENT TO PARTICIPATE

Written informed consent was obtained from all subjects before inclusion.

ORCID

Tjerk S. O. Sleeswijk Visser https://orcid.org/0000-0002-4483-1936

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