Article

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Ultrasound Shear Wave Elastography of the Arch-Supporting Structures in Symptomatic Flatfoot: A Pilot Study

L. Daniel Latt, MD, PhD[1], Wonsuk Kim, MD[2], Chelsea C. Caruso, DO[2], Elizabeth A. Krupinski, PhD[3], Andres Angel Nuncio Zuniga, BS[2], Amit Syal, BS[4], and Mihra S. Taljanovic, MD, PhD[1,5]

Abstract

Background: The posterior tibial tendon (PTT), deltoid ligament, and spring ligament are often torn or attenuated in patients with progressive collapsing foot deformity. The goal of this pilot study was to measure the ultrasound shear wave velocity (SWV) of these arch-supporting structures in feet with varying degrees of deformity to improve our understanding of their role in the progression of deformity.
Methods: Two observers measured the SWV of the supramalleolar and inframalleolar PTT in long and short axes, in the tibiospring portion of the deltoid ligament, and in the superomedial band of the spring ligament in 8 neutrally aligned feet, 5 asymptomatic flatfeet, and 7 symptomatic flatfeet. Each measurement was repeated 3 times both with and without an applied eversion stress.
Results: Average SWV was lower at all locations in the symptomatic flatfeet compared with normal feet, but these differences were statistically significant only for the inframalleolar PTT and the spring ligament. Externally applied stress led to an increase in the SWV of the ligaments but a paradoxical decrease in the SWV in the supramalleolar PTT. The SWV of the PTT was lower along the short axis compared with the long axis.
Conclusion: SWV may be useful in evaluating the severity of degenerative disease of arch-supporting structures, but further study is needed before this technique can be applied clinically.

Level of Evidence: Level III, case-control study.

Keywords: posterior tibial tendon, spring ligament, shear wave velocity, elastography, adult acquired flatfoot deformity, progressive collapsing foot deformity

Introduction

Adult acquired flatfoot deformity, recently renamed as progressive collapsing foot deformity (PCFD), was classically thought to involve degeneration, dysfunction, and insufficiency of the posterior tibial tendon (PTT), and thus it was originally called posterior tibial tendon dysfunction.[22] Recent work has focused on the role of the arch- and hindfoot-supporting ligaments including the calcaneonavicular (spring) and deltoid ligaments.[6] However, the progression of injury to these structures with advancing disease has not been well characterized. Specifically, the time course of the deterioration of these structures relative to the onset of the

[1]Department of Orthopaedic Surgery, University of Arizona, Tucson, AZ, USA
[2]Department of Medical Imaging, University of Arizona, Tucson, AZ, USA
[3]Department of Radiology, Emory University, Atlanta, GA, USA
[4]Sidney Kimmel Medical College at Thomas Jefferson University, Philadelphia, PA, USA
[5]Department of Medical Imaging, University of Arizona, Tucson, AZ, USA

Corresponding Author:
L. Daniel Latt, MD, PhD, Department of Orthopaedic Surgery, University of Arizona, 1609 N. Warren Ave, Tucson, AZ 85719, USA.
Email: danlatt@gmail.com

symptoms or development of deformity is not known. There likely exists a spectrum of disease from a neutrally aligned foot to asymptomatic flatfoot and to symptomatic flatfoot. A comparison of the material properties of the arch-supporting structures across this spectrum may provide insight into the relationship between ligament or tendon degeneration and the development of deformity in PCFD and thus might enable earlier diagnosis and treatment prior to the development of collapse.

Ultrasound (US) shear wave elastography (SWE) is a noninvasive technique for quantifying the in vivo material properties of tendons[5,17] and other musculoskeletal soft tissues.[28] The US shear waves create local stress and displacement within the tissues, which are measured by the US transducer and displayed as a color-coded elastogram of shear wave velocities (SWVs, in m/s) or tissue elasticity (in kPa).[3] SWE has been used in the evaluation of various musculoskeletal tissues including muscles,[8,20,26,29] tendons,[1,2,4,5,7,10,15,17-19,33] ligaments,[3,10,12,14,21,25,27,32] and plantar fascia.[3,9,16,23,24,30,31] However, there have been only a few investigations of the medial[25] or lateral ankle ligaments.[10,27]

One challenge with the use of SWE in musculoskeletal tissues is that the measured velocities vary with tissue tension, with greater values measured from tissues under tension. A recent study[10] of the lateral ankle ligaments compared the SWE velocities at rest with those under stress and found a significant difference in SWE velocities between the relaxed and stressed conditions. If SWE is to be used to evaluate the arch-supporting structures, the technique for their measurement should include a protocol for how to control the externally applied load to ensure consistent stress within the structures during measurement.

The primary goal of this study was to evaluate differences in SWE velocities of the PTT, the deltoid ligament, and the spring ligament between individuals with a neutrally aligned foot, an asymptomatic flatfoot, and a symptomatic PCFD to determine if there is a relationship between the progression of flatfoot deformity and in vivo material properties of the arch-supporting structures. The secondary goal was to determine if there are differences when measuring the SWV of these tissues at rest as compared with those under stress and, if so, to standardize the protocol for applying the external load. We hypothesize that the SWV of the arch-supporting structures will decrease with increasing severity of arch collapse. Furthermore, we hypothesize that the SWVs will show larger differences between groups when measured under applied stress as compared with when measured in the relaxed state.

Materials and Methods

We conducted a pilot study comparing SWE velocities of the arch-supporting structures between individuals with a neutrally aligned foot, an asymptomatic flatfoot, and a symptomatic flatfoot (PCFD). Inclusion criteria were age 18-80 years, no previous foot or ankle surgery, and no diabetes mellitus. The determination of foot alignment was made on weightbearing lateral radiographs in which a Meary angle (the angle between the long axes of the talus and the first metatarsal) >10 degrees was considered flatfoot and ≤ 10 degrees neutral.[13] Participants were considered to have symptomatic flatfoot if they met the flatfoot criteria, had been previously diagnosed with stage II (flexible) acquired flatfoot deformity/posterior tibial tendon dysfunction, and had symptoms of pain and swelling of either the PTT or the peroneal tendons and were thus unable to do a single leg heel rise.[13] The asymptomatic flatfoot group was used to determine whether any identified differences in SWV were related to the symptomatic degeneration or simply the foot alignment.

Ten individuals participated in this single-day institutional review board–approved study. They were recruited from the clinical practice of the senior author and were not paid for their participation in the study. There were 8 neutrally aligned feet (“Neutral”) in 4 participants, 5 asymptomatic flatfeet (“Asymptomatic”), and 7 symptomatic flatfeet (“Symptomatic”) in the 6 flatfoot participants. Six of the 10 subjects were females ranging in age from 28 to 53 years. The other 4 patients were males aged 22-61 years.

The US SWE examination was performed by a musculoskeletal fellowship-trained radiologist with more than 25 years of experience (observer 1) and a musculoskeletal radiology fellow (observer 2) on a Siemens S300 ultrasound machine (Erlangen, Germany) with a 9-MHz linear transducer. The 2 observers performed SWE of the PTT in both long and short axes at both the supramalleolar (“PTT upper”) and inframalleolar (“PTT lower”) locations, the tibiospring portion of the superficial deltoid ligament (“Deltoid”), and the superomedial band of the spring ligament (“Spring”) without externally applied stress. SWVs were obtained from 3 locations within each structure and each measurement was repeated 3 times (Figures 1 and 2). Between observers, the subject was asked to relax and then reposition their foot in the same externally rotated position to expose the medial side of the hindfoot and ankle. Following the unloaded trials, the first observer then repeated the measurements of the PTT upper long axis, deltoid, and spring 3 times with stress applied externally to the tendon and ligaments by a fellowship trained orthopaedic foot and ankle surgeon (L.D.L.). External stress was applied to the PTT by positioning the foot in maximal eversion and then asking the subject to actively invert against the dynamometer through which the examiner applied eversion force. External stress was applied to the deltoid spring ligament complex by passively everting the hindfoot maximally and then continuing to apply eversion stress until the desired force level was reached. A myometer with real-time force measurement was used to maintain the externally applied

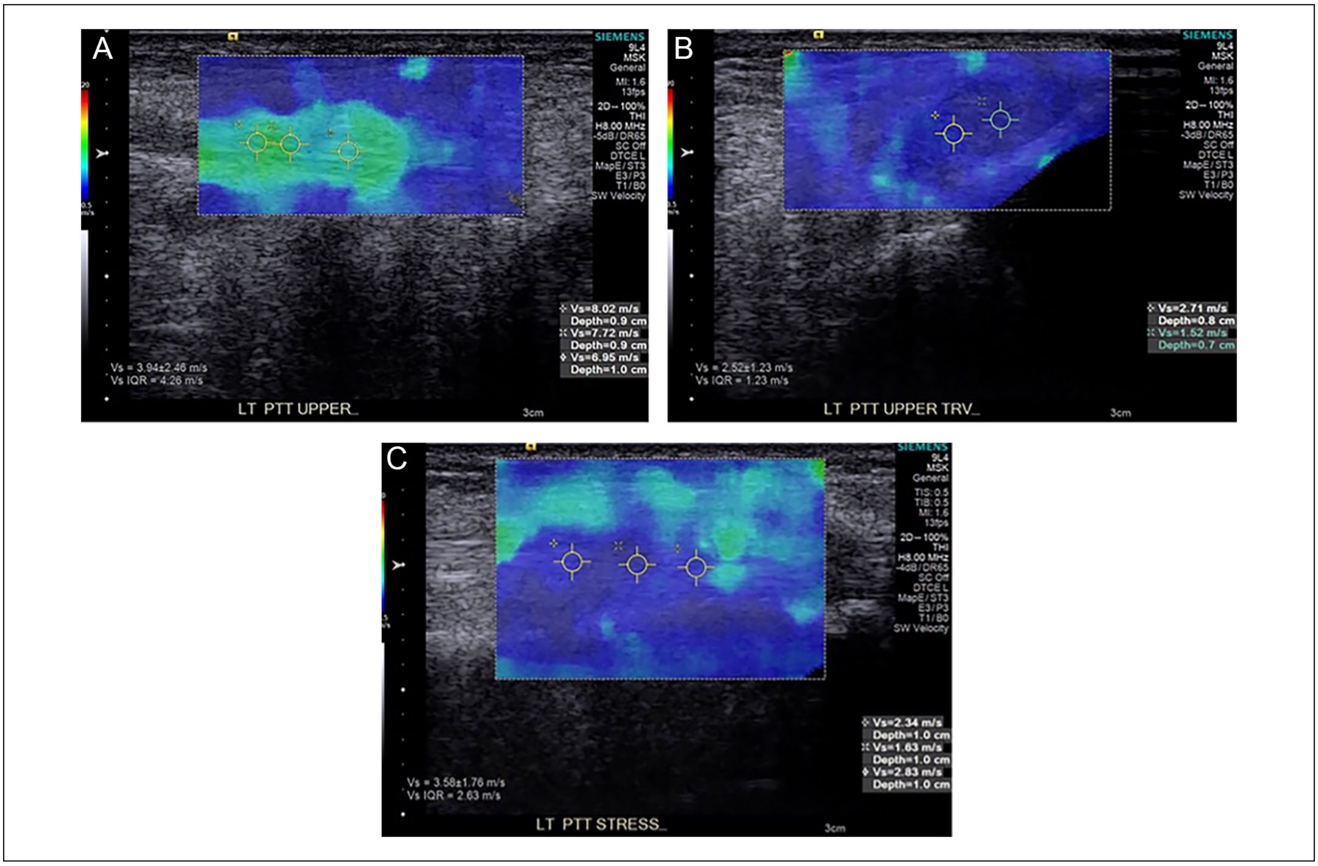

Figure 1. Representative ultrasound shear wave elastography (US SWE) images of the supramalleolar (upper) posterior tibial tendon in an asymptomatic flatfoot. (A) Long axis US SWE image at rest demonstrates intermediate shear wave velocities (SWVs) in green. (B) Short axis (transverse) US SWE image in the same region at rest shows lower SWVs in blue. (C) Under stress, long axis US SWE image in the same region shows decreased SWVs in blue.

force at 100 ± 10 N (Figure 3; myometer not shown for clarity of images).

The ratings for the 2 observers were compared using the intraclass correlation coefficient and a Bland-Altman plot. A 2-way analysis of variance was used to evaluate the effect of deformity (neutral/asymptomatic/symptomatic) and stress (at rest/under stress) on SWV for each measurement location. The effect of stress condition on SWV for each location pooled across groups was then compared using paired *t* tests. A *P* value $<.05$ was considered to be statistically significant.

Results

The intraclass correlation coefficient comparing the ratings of the 2 observers was 0.9134 (95% CI 0.8769-0.9391), demonstrating high overall agreement (Table 1), and a Bland-Altman plot showed overall high consistency (Figure 4). Thus, the scores from the 2 observers were averaged.

The mean SWV in all tissues was lower for the symptomatic flatfeet as compared with the neutrally aligned feet; however, the analysis of variance evaluating the effect of deformity and stress on SWE velocity (Table 2 and Figure 5) failed to identify any significant independent factors. The effect of deformity approached significance for the PTT lower long axis at rest and the spring ligament at rest. The PTT upper long axis and the tibiospring deltoid ligament were found to have decreasing SWV with increasing deformity, although these trends were not significant because of the large SDs. When the groups were then pooled and the effect of stress examined for each measurement location using *t* tests (Table 3), the PTT upper long axis was found to have significantly lower SWE velocity under stress than at rest.

Discussion

The principal objective of this study was to compare the material properties of the arch-supporting soft tissues across a range of deformities to discern whether there is a relationship between the material properties of the arch-supporting structures and the extent of arch collapse. Unfortunately, we

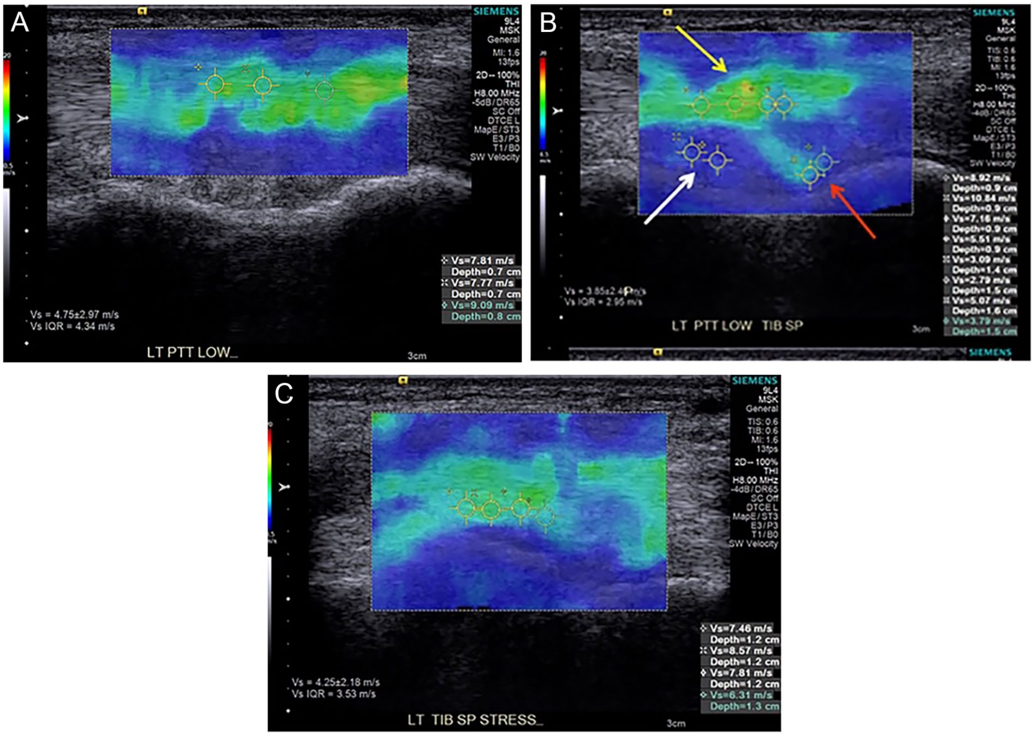

Figure 2. Representative ultrasound shear wave elastography images of the inframalleolar (lower) posterior tibial tendon (PTT), subjacent superficial deltoid ligament (tibiospring portion), and spring ligament (superomedial band) in an asymptomatic flatfoot, at rest (A and B) and under stress (C). The individual structures are identified in (B): long axis of the PTT (yellow arrow), tibiospring portion of the deltoid ligament (white arrow), and superomedial band of the spring ligament (red arrow). At rest note intermediate shear wave velocities (SWVs) in the PTT in green (A and B), lower SWVs in the tibiospring ligament in blue, and intermediate to low SWVs in the superomedial band of the spring ligament in lighter green and blue (B). Increased intermediate SWVs are seen in the tibiospring deltoid ligament in green when imaged under stress (C).

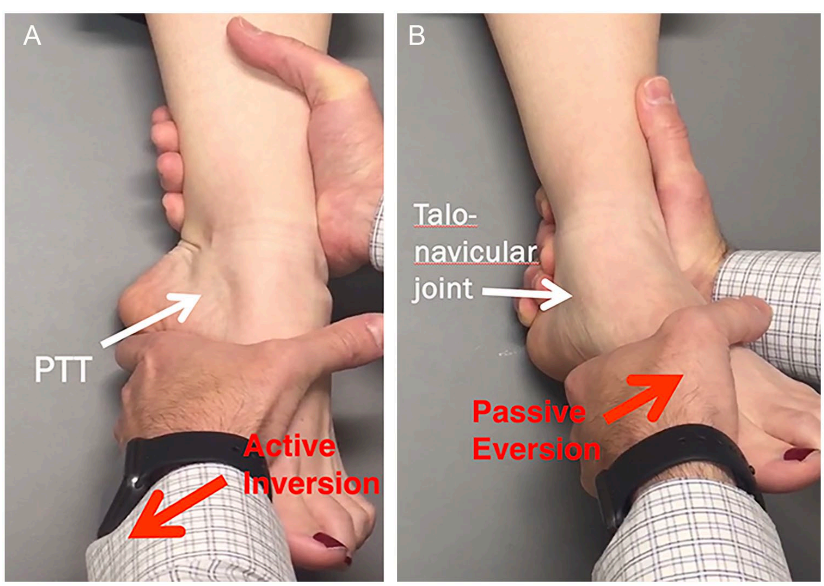

Figure 3. Application of manual external stress to (A) the posterior tibial tendon with resisted active inversion in maximal plantar flexion and (B) the spring ligaments using passive maximal eversion of the talonavicular and subtalar joints.

Table 1. The ICC and 95% CI Between the 2 Observers.

Structure	ICC	95% CI
PTT upper long axis	0.9140	0.7880 to 0.9651
PTT lower long axis	0.8427	0.6125 to 0.9362
PTT upper short axis	0.5938	−0.0011 to 0.8352
PTT lower short axis	0.6593	0.1603 to 0.8618
Deltoid ligament	0.7545	0.3951 to 0.9004
Spring ligament	0.7160	0.3000 to 0.8848

Abbreviation: ICC, intraclass correlation coefficient; PTT, posterior tibial tendon.

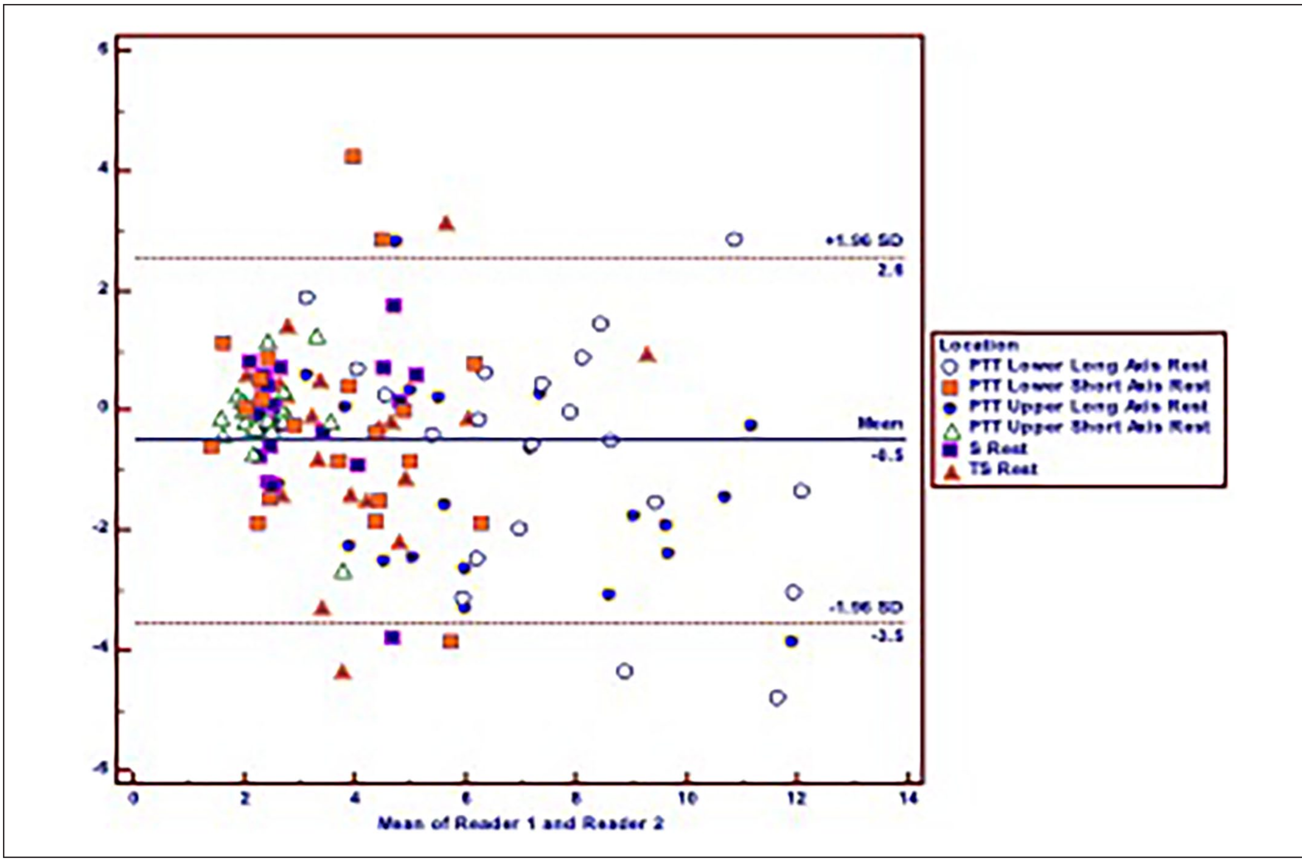

Figure 4. Bland-Altman plot of the ratings of the 2 observers for each of the measured variables shows high overall consistency.

did not find a pattern of change in SWV with progressing deformity that was consistent across all the tissues examined and thus are unable to confirm our main hypothesis. However, we did find some inconsistent patterns that were not statistically significant with a trend toward lower SWE velocities with increasing deformity. For instance, we found lower SWVs with increasing deformity in the PTT upper long axis. Other studies that used SWE to evaluate injured or degenerated tendons found lower SWVs in those with tendinopathy[1] and tears.[4] We also found a trend toward decreasing SWVs in the deltoid ligament with increasing deformity both at rest and with stress. This is consistent with the findings of previous studies that have demonstrated significant decreases in tissue stiffness and SWV associated with ligament degeneration.[3]

In contrast, we found higher SWVs in the inframalleolar PTT in asymptomatic flatfeet compared with those with neutrally aligned or symptomatic flatfeet. This finding has not been described in the literature and may be related to increased distal tendon loading in the preclinical stage of disease as the tibialis posterior is supporting a collapsing arch. PTT overload could be used as an early indicator of impending collapse. We also found that SWV depended on probe orientation with higher velocities along the long axis

Table 2. US SWV Mean (SD) at Rest and Under Stress for Neutral, Asymptomatic, and Symptomatic Feet.

Condition	Structure	Neutral	Asymptomatic	Symptomatic	*F* Statistic	*P* Value
At rest	PTT upper long axis	7.49 (3.41)	6.84 (2.57)	6.04 (2.37)	0.477	.639
	PTT lower long axis	7.86 (2.16)[a]	9.67 (1.90)[a]	6.33 (2.77)[a]	2.97[a]	.079[a]
	PTT upper and lower short axes	3.28 (0.92)	3.01 (0.93)	2.75 (0.99)	0.581	.570
	Deltoid ligament	4.27 (1.42)	3.97 (2.97)	3.54 (0.71)	0.328	.725
	Spring ligament	3.66 (1.21)[a]	2.41 (0.10)[a]	2.86 (0.81)[a]	3.161[a]	.068[a]
Under stress	PTT upper long axis	3.52 (2.79)	2.89 (1.37)	2.13 (0.41)	0.841	.450
	Deltoid ligament	4.59 (2.69)	3.42 (053)	3.35 (3.23)	0.340	.718
	Spring ligament	3.49 (1.10)	2.39 (0.49)	3.24 (1.30)	1.734	.208

Abbreviations: PTT, posterior tibial tendon; SWV, shear wave velocity; US, ultrasound.
[a]Spring ligament at rest and PTT lower long axis at rest approached significance; the others were not significantly different.

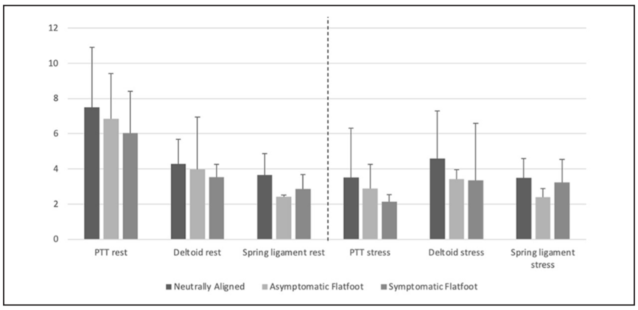

Figure 5. SWE velocity means at rest and under stress for neutrally aligned, asymptomatic, and symptomatic tendons. PTT rest represents PTT upper long axis at rest. Error bars correspond to SD. PTT, posterior tibial tendon; SWE, shear wave elastography.

of healthy tendons than along their short axis, which agrees with previous studies[1] and is likely related to the anisotropy of tendons in which the tendon fibers run parallel to the long axis of the tendon. Future SWE studies of the tendons will likely overcome this problem by mapping SWVs in 3D.[11]

Our secondary objective was to determine the impact of tissue stress during the measurement of SWV and to develop a protocol for externally applying the load in a consistent fashion. We found that the superomedial band of the spring ligament showed higher SWVs under stress than in relaxed states across all 3 groups, but in this small number of subjects, this did not reach statistical significance. However, we also found that shear waves propagated more slowly in PTT under stress, which is in contrast with the literature in which there is consensus that shear waves propagate faster in stretched tendons[1,2] and contracted muscles.[26,29] This discordance raises the possibility that the PTT was paradoxically unloaded in our study during manual stress. This could have occurred if the subjects substituted tibialis anterior tendon while performing resisted inversion of the midfoot or forefoot on the hindfoot.

Finally, we had hoped to develop a protocol for applying a consistent stress to ligaments and tendons during SWE. Various methods have been used to apply external stress. A common technique is to use changes in joint angle to produce a stretch in the tendon[1,8] or ligament.[25] A disadvantage of using the joint position is that the applied load in the tendon or ligament will vary with the subject's anatomy. An alternative strategy, used in this study as well as in previous work on lateral ankle ligaments, is to use a handheld dynamometer to apply a near-constant external force using continuous measurement, which allows the examiner to adjust the applied load.[10] The potential advantages of this alternative method of improved consistency during measurements made under stress were not realized in this study.

Limitations

The principal limitation of this pilot study was its small sample size and large intersubject variability that prevented us from performing the planned subgroup analyses. A larger sample size in a future study is needed to make such analyses feasible. Additional subjects were not recruited to this study because collecting another round of data during a separate session might add another source of variability and could potentially introduce a performance bias. The second limitation is that we examined only a few of the arch-supporting structures. The plantar fascia, long plantar, and short plantar ligaments are also known to be important arch-supporting structures and are thus also potential targets for the early detection of arch collapse. The final limitation is that we did not explore changes with tendon or ligament degeneration over time but instead chose to perform a cross-sectional study in which the neutrally aligned, asymptomatic flatfoot, and symptomatic flatfoot are assumed to represent the no disease, preclinical disease, and diseased states.

Conclusion

We found some differences in the SWVs of the arch-supporting soft tissues between individuals with neutral alignment, asymptomatic flatfoot, and symptomatic flatfoot, but we were unable to identify a clear and consistent pattern in

Table 3. Comparison of SWE Values at Rest vs Under Stress Pooled Across All Feet.[a]

Structure	At Rest	Under Stress	*T* Statistic	*P* Value
PTT upper long axis	6.74 (2.76)[b]	2.85 (1.94)[b]	6.46	<.0001
PTT lower long axis	7.71 (2.53)	Not tested		
PTT upper short axis	2.41 (0.58)	Not tested		
PTT lower short axis	3.70 (1.49)	Not tested		
Deltoid ligament	3.94 (1.65)	4.42 (2.57)	0.643	.528
Spring ligament	3.14 (1.04)	3.32 (1.40)	0.543	.594

Abbreviations: PTT, posterior tibial tendon; SWE, shear wave elastography.
[a]PTT lower long, upper short, and lower short axes were not measured under stress.
[b]Only PTT upper long axis was significantly different between the stressed and unstressed conditions.

this pilot study. In particular, the SWV of the inframalleolar PTT was larger in individuals with asymptomatic flatfoot, which may serve as a warning of impending tendon failure. US SWE may be a useful adjunct in evaluation and management of patients with PCFD, with the possibility to detect a preclinical stage of disease and thus enable earlier intervention prior to the development of deformity and symptomatic disease. However, further studies involving more participants at various stages of arch collapse are needed to clearly define the SWV of the arch-supporting structures across the spectrum of disease.

Ethical Approval

The study was conducted according to the guidelines of the Declaration of Helsinki and approved by the Institutional Review Board of the University of Arizona (protocol no. 1000000966; approved on January 8, 2014).

Declaration of Conflicting Interests

The author(s) declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article. Disclosure forms for all authors are available online.

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Informed Consent Statement

Informed consent was obtained from all subjects involved in the study.

ORCID iD

L. Daniel Latt, MD, PhD, https://orcid.org/0000-0002-9925-3440

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