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The shear mechanical properties of diabetic and non-diabetic plantar soft tissue

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Abstract

Changes in the plantar soft tissue shear properties may contribute to ulceration in diabetic patients, however, little is known about these shear parameters. This study examines the elastic and viscoelastic shear behavior of both diabetic and non-diabetic plantar tissue. Previously compression tested plantar tissue specimens ($n = 54$) at six relevant plantar locations (hallux, first, third, and fifth metatarsal heads, lateral midfoot, and calcaneus) from four cadaveric diabetic feet and five non-diabetic feet were utilized. Per *in vivo* data (i.e., combined deformation patterns of compression followed by shear), an initial static compressive strain (36–38%) was applied to the tissue followed by target shear strains of 50% and 85% of initial thickness. Triangle waves were used to quantify elastic parameters at both strain levels and a stress relaxation test (0.25s ramp and 300s hold) was used to quantify the viscoelastic parameters at the upper strain level. Several differences were found between test groups including a 52–62% increase in peak shear stress, a 63% increase in toe shear modulus, a 47% increase in final shear modulus, and a 67% increase in middle slope magnitude (sharper drop in relaxation) in the diabetic tissue. Beyond a 54% greater peak compressive stress in the third metatarsal compared to the lateral midfoot, there were no differences in shear properties between plantar locations. Notably, this study demonstrates that plantar soft tissue with diabetes is stiffer than healthy tissue, thereby compromising its ability to dissipate shear stresses borne by the foot that may increase ulceration risk.

Keywords

foot; diabetes; subcutaneous; ulceration; viscoelastic

Introduction

The risk of plantar ulceration, and subsequent amputation, is disproportionately increased in the diabetic population (CDCP, 2011). Improving ulcer prevention measures requires a better understanding of any underlying detrimental plantar soft tissue changes induced by

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Conflict of Interest Statement

The authors have no conflicts to report.

this disease. Specifically, knowledge of mechanical property alterations under relevant plantar loading, i.e., compression and shear, is needed. Our group and several others have examined diabetes-induced changes in the compressive elastic (Pai and Ledoux, 2010; Cheung et al., 2006; Gefen et al., 2001; Hsu et al., 2009; Hsu et al., 2007; Hsu et al., 2002; Hsu et al., 2000; Klaesner et al., 2002; Piaggesi et al., 1999) and viscoelastic (Pai and Ledoux, 2011) parameters of the plantar soft tissue. However, little is known about alterations in the plantar soft tissue shear properties despite the fact that shear loading beneath the foot is estimated to be between one half and one seventh of the vertical peak loads depending on plantar location (Hosein and Lord, 2000; Yavuz et al., 2008). A recent study (Yavuz et al., 2008) indicates increased shear loading with diabetes, thereby further motivating the need to study shear properties. Additionally, increased shear stresses at certain plantar locations or regions may play a role in ulceration (Yavuz et al., 2007; Zou et al., 2007).

Beyond shear stress, little is known about the plantar soft tissue shear properties. One group measured the *in vivo* shear modulus of the subcalcaneal soft tissue using MR elastography imaging and found that the shear modulus increased from 8kPa to 12kPa with increasing pressure (Weaver et al., 2005). These results provide a first approximation of the shear properties of plantar tissue but examined one plantar location, used small shear deformations (20 μ m), and did not study the effect of diabetes.

A common approach to induce a state of shear in many soft tissues is through torsion tests of cylindrical samples using standard rheology equipment (Bilston et al., 1997; Holt et al., 2008; Iatridis et al., 1999; Iatridis et al., 1997; Liu and Bilston, 2002; Shuck and Advani, 1972). Staying within the linear elastic range allows for computation of the complex modulus. However, this approach is limited for large strains that are not within the linear elastic region, such as those observed in the plantar soft tissue. Another common shear testing approach is the simple shear method whereby the tissue being sheared is sandwiched between two parallel plates before applying a lateral or shear displacement (Arbogast and Margulies, 1998; Carew et al., 1999; Chan and Rodriguez, 2008; Darvish and Crandall, 2001; Hayes and Bodine, 1978; Prange and Margulies, 2002; Tanaka et al., 2008). Although sometimes used for small strain experiments, this method is also able to conduct large strain studies that better represent the *in vivo* plantar soft tissue shear strains

While previous estimates for plantar shear loads (Yavuz et al., 2007; Yavuz et al., 2007; Yavuz et al., 2008) could be used to apply biomechanically realistic deformations during *in vitro* mechanical tests using the simple shear method, it remains unclear whether any adjustment to account for isolating the plantar soft tissue would be needed. Further, it is unclear what shear strains would correspond to these shear loads. We recently measured the *in vivo* plantar soft tissue shear strains using fluoroscope imaging in one healthy subject (Pai, 2011); these strains would be ideal for applying realistic deformations.

Thus, the purpose of this study is to examine the elastic and viscoelastic shear behavior of both diabetic and non-diabetic plantar tissue at relevant locations beneath the foot using biomechanically realistic testing methods with previously obtained shear strains as input. Characterizing these shear properties is essential to fully understanding the role, if any, that shear property changes play with ulcer formation in diabetic patients.

Methods

Experimental protocol

Plantar tissue specimens (n = 54) at six plantar locations (Fig. 1, hallux, first, third, and fifth metatarsal heads, lateral midfoot, and calcaneus) from four fresh frozen cadaveric older

diabetic feet (20.3 ± 8.1 yrs post-diagnosis) and five non-diabetic older feet (Table 1) were used in this study. These specimens were previously dissected and tested in compression (Pai and Ledoux, 2010, 2011) after which they had been wrapped in saline soaked paper towels, placed in a plastic box, vacuum sealed, and refrozen (-20°C). Specimens were repunched while still frozen (reduced to a 12.7mm diameter to prevent load cell overload) and cut (to prevent buckling) using a custom guillotine (Fig. 1) to a uniform initial thickness. Specimens were then placed in an environmental chamber at 100% humidity and 35°C and adhered to the platens attached to the material shear tester (Mach-1, Biomomentum, Laval, Quebec, Canada) using cyanoacrylate to prevent specimen slippage during testing (Fig. 2). The top platen was lowered to apply a nominal preload (0.1N) on the specimen before initial thickness was measured. The material tester had a displacement resolution of $0.1\mu\text{m}$ for both compression and shear axes and the six-axis load cell had a resolution of 3.5mN in compression and 2.5mN in shear. Further, the calibrated displacement accuracy was within 0.0016% and 0.0025% of full scale for the compression and shear axes respectively and the calibrated load cell accuracy was within 1% of full scale for all axes.

A static compressive load was applied prior to shearing the tissue to emulate *in vivo* combined loading patterns. The target load was based on specimen area, donor weight, normative ground reaction force and contact area (Ledoux and Hillstrom, 2002), and isolation effects from dissecting surrounding tissue away (Miller-Young and Duncan, 2002). Similar to our previous compression tests of the plantar soft tissue (Pai and Ledoux, 2010, 2011), the target static compressive load was applied to determine a target strain. However, in the present study static compressive load was applied in displacement control rather than load control using a specialized feature of the material tester software (Mach-1 Motion, Biomomentum, Laval, Quebec, Canada). Further, to minimize stress softening only two cycles were used to determine the target compressive strain.

Biomechanically realistic shear strains were estimated using *in vivo* fluoroscope images of barefoot gait for a healthy adult (Caucasian male, 41 years, 1.83m, 95.3kg, US men's shoe size 12, self-selected walking speed) in a previous study (Pai, 2011). The target shear strains were determined for various plantar locations (hallux, first and fifth metatarsal heads, base of fifth metatarsal/lateral midfoot, and calcaneus) to be between 50% and 85% of initial thickness (equivalent to a shear strain angle of 30° to 55° with respect to loaded thickness). For the mechanical testing, both strains were tested sequentially. Using 50% target shear strain, the static compression to the target compressive strain was followed by 14 triangle waves (ten cycles to allow for preconditioning) at a frequency of 1Hz to the 50% shear strain. After a five minute recovery period, a second test was conducted using 85% target shear strain. Another five minute recovery period was allowed before performing a shear stress relaxation test consisting of static compression to the target compressive strain immediately followed by a 0.25s ramp and 300s hold to the 85% target shear strain.

Nonlinear elastic parameters for each shear strain level were computed as well as viscoelastic parameters for each relaxation test (Matlab 7.1, The MathWorks, Inc., Natick, MA). Elastic parameters were quantified from the 11th, 12th, and 13th triangle wave stress-strain hysteresis curves including and peak and base compressive stress (max and min compressive force divided by original specimen area), peak shear (max force divided by original specimen area), peak strain (max displacement divided by initial specimen thickness), initial, toe, and final modulus (slopes of the loading curve between inflection points), and energy loss (area between the loading and unloading curves). The relaxation force data were used to quantify several viscoelastic parameters including slopes of the curve (i.e., relaxation rate) at three time intervals, initial ($t = 0$ to 0.5s), mid ($t = 10$ to 15s), and final ($t = 290$ to 300s) slopes, and the normalized curve area to compare relative total relaxation.

Statistical analysis

Linear mixed effects regression was used to determine if specimen parameters differed by disease status and location. To determine differences in elastic parameters with multiple repeated measures levels, linear mixed effects regression was used. Significance was set at $p = 0.05$. Linear mixed effects regression was used to determine if relaxation parameters differed by diabetes status and location of specimen. Pair-wise comparisons were conducted with significance set at $p = 0.0036$ (0.05/14 possible comparisons) using Bonferroni's correction. Analyses were carried out using R 2.11.1 (R-Development-Core-Team, 2010) using the lme4 package (Bates and Maechler, 2010).

Results

No differences were found between specimen parameters by disease status (Table 2). Examination of the shear stress-strain response for specimens from all locations in a sample non-diabetic foot showed a nonlinear S-shaped curve for both the 50% and 85% shear strain data (Fig. 3). Comparison of curves in one specimen at both strain levels indicated a longer toe region with reduced stress for the same strains in the second test group at 85% strain, indicating stress softening effects, yet higher overall peak stress (hence the higher strain level was able to overcome some of the softening effects). Since we are primarily interested in differences due to disease status and plantar location, all results were grouped together for both strain levels and due to stress softening effects, differences between strain levels were not examined.

Several differences were found between diabetic and non-diabetic shear elastic parameters (Table 3) including increased diabetic peak shear stress, toe shear modulus, and final shear modulus. Although peak compressive stress was not significantly different between groups, it was borderline higher in the diabetic tissue (due to increased donor body weight and hence target load). Of note, there were variations in the static compressive stress for the elastic data, as quantified by the peak and base compressive stresses (Table 3) and seen in sample triangle waves for one specimen (Fig. 4). This cyclic variation in compressive load with each shear displacement cycle is likely due to the incompressible nature of the plantar soft tissue, causing the tissue to fold/bulge over itself during shear and thereby inducing an additional compressive peak above the statically applied base compressive load.

There were no differences between specimen parameters by plantar location (Table 4) or for elastic parameters (Table 5).

The stress relaxation behavior of both the diabetic and non-diabetic tissue was very similar when averaged, although both test groups demonstrated considerable inter-specimen variability (Fig. 5). Further, the near linear response in the stress versus log time plot showed that there was little frequency-sensitive damping. Thus, few differences were found in the viscoelastic parameters by disease status (Table 6). Of note, the peak shear stress and middle slope were greater in the diabetic tissue, indicating stiffer tissue with a less viscous response (sharper drop in relaxation). Additionally, the peak compressive stress was higher in the diabetic tissue (due to increased donor body weight and hence target load).

The stress relaxation behavior across plantar soft tissue locations was very similar when averaged (Fig. 6), although all specimen locations demonstrated considerable inter-specimen variability (Fig. 7). Similar to the comparison by disease status, the near linear stress versus log time response showed that there was no apparent frequency-sensitive damping in shear. Based on the similarity in stress relaxation behavior, almost no changes were seen in the viscoelastic parameters across plantar soft tissue locations (Table 7). The overall differences across all locations were between peak compressive stress as well as middle slope, although

there were non-significant trends for peak shear stress and initial slope. However, post-hoc analyses revealed only one difference: peak compressive stress was greater in the third metatarsal compared to the lateral midfoot (despite no difference in compressive strain or other specimen parameters across locations, see Table 4).

Discussion

Characterizing the plantar soft tissue shear properties is essential to fully understanding the role that diabetes plays in ulcer formation in diabetic patients at-risk for ulceration. This study examines the elastic and viscoelastic shear behavior of both diabetic and non-diabetic plantar tissue at relevant locations beneath the foot by applying previously obtained *in vivo* shear strains in simple shear.

Several differences were found between diabetic and non-diabetic shear elastic and viscoelastic properties. In terms of elastic parameters, a 52% increase in peak shear stress, a 63% increase in toe shear modulus, and a 47% increase in final shear modulus were observed in the diabetic tissue. These results indicate that diabetic plantar soft tissue is stiffer in shear, which coincides with our previous observations in compression (Pai and Ledoux, 2010) as well as previous *in vivo* indentation studies (Gefen et al., 2001; Hsu et al., 2009; Klaesner et al., 2002; Zheng et al., 2000). This increased shear stiffness would make diabetic tissue less able to dissipate stresses, which could increase ulceration risk. In terms of viscoelastic parameters, although the stress relaxation behavior of both the diabetic and non-diabetic tissue appeared very similar when averaged, a 62% increase in the peak shear stress and 67% increase in middle slope magnitude (sharper drop in relaxation) were observed for the diabetic tissue. These results further indicate stiffer diabetic tissue as well as faster relaxation. Additionally, the peak compressive stress in the relaxation test was 40% higher in the diabetic tissue; this result was anticipated due to increased donor body weight and hence target load. Although peak compressive stress was also 44% higher in the diabetic tissue for the triangle wave/elastic data, the difference was a non-significant trend ($p = 0.063$, likely due to inter-specimen variability).

There were almost no differences in shear properties between plantar locations. For the elastic parameters, no differences were found by location similar to our previous findings in compression (Pai and Ledoux, 2010) where almost no differences were found. This lack of location-specific differences in elastic properties for both shear and compression parameters should be interpreted with caution as the limited sample size in our studies may not capture very subtle differences in tissue properties. Similarly, the mean shear stress relaxation behavior across plantar soft tissue locations resulted in almost no changes in the corresponding viscoelastic shear parameters, coinciding with our previous study in compression (Pai and Ledoux, 2011) which found no differences in viscoelastic parameters. The only difference between locations in the current study was not for a shear parameter but instead for the initially applied static load that yielded a 54% greater peak compressive stress in the third metatarsal compared to the lateral midfoot. Although this difference was surprising, since there was no difference in compressive strain or other specimen parameters across locations, it is of little consequence since it does not reflect the tissue shear properties.

Further, there were some stress softening effects in the plantar soft tissue in shear. Stress softening is associated with large reductions in stress at a given strain level during successive cycles compared to the stress on initial loading (Horgan et al., 2004). Qualitative comparison of the elastic response at both strain levels indicated reduced stress at the same strain in the loading curves for the larger 85% strain level test group, indicating stress softening effects since this level was tested after the 50% strain level. Thus, all results were

grouped together for both strain levels and differences between strain levels were not examined. Interestingly, peak compressive stress was higher in the viscoelastic relaxation data than the elastic triangle data (although significance was not tested) even though the relaxation tests were performed last and to the same compressive strain. This unexpected result could possibly be due to the faster ramp time for the relaxation data, equivalent to a 2Hz triangle wave. Also, the tissue was allowed to recover for five minutes before directly applying the ramp and hold whereas the triangle wave data had ten preconditioning cycles before the actual analyzed data, which would have resulted in more stress softening in the latter case.

Qualitative comparison of the current shear results with those previously obtained in compression showed considerable differences. The elastic shear stress-strain response for all specimens was nonlinear with an S-shaped curve due to a short initial highly stiff region at low strains, a long low stiffness toe region, and a final stiff region at higher strains for both strain levels. In contrast, the stress-strain response in compression has a J-shaped response with only one inflection point (Pai and Ledoux, 2010; Ledoux and Blevins, 2007). Further, although no attempts were made to fit the data to the quasi-linear viscoelastic theory (due to previously observed limitations of this model (Pai and Ledoux, 2011)), the near linear response in the stress versus log time plot indicated that unlike compression (Pai and Ledoux, 2011), there is little frequency-sensitive damping in shear.

Comparison of our work to previous estimations of shear properties is difficult since to our knowledge there are no other *in vitro* shear mechanical tests of the plantar soft tissue. Previous measurements of the *in vivo* shear modulus of the subcalcaneal soft tissue using MR elastography ranged from 8kPa to 12kPa (Weaver et al., 2005) whereas our results, with much larger strains, ranged from 18kPa to 124kPa depending on the region of the stress-strain curve. Previous measurements of the *in vivo* peak plantar shear stress for diabetic subjects ranged from 67kPa to 79kPa in one study (Zou et al., 2007) and was 83kPa in another (Yavuz et al., 2008) in comparison to our diabetic peak shear stress which was only 24kPa. This difference is not surprising, given that our results are based on isolated plantar soft tissue specimens rather than intact feet.

The limitations of this study include that neither the shear strain-rate sensitivity of the tissue nor the medial-lateral shear properties were examined since we did not want to over-test the specimens. Additionally, the stress relaxation data was not fit to a constitutive model; instead, raw data parameters were used to quantify the relaxation data for comparisons between test groups. Due to stress softening between strain levels, all the data was grouped together. It was not possible to test some specimens to the lower strain level and others to higher level since this would have reduced the number of specimens (since they would have been divided for each strain level) and for fear of damaging the load cell by immediately testing to the larger strain level. Further, since the shear strains used in the mechanical tests were measured from a healthy subject's foot, they may not be representative of shear strains experienced by diabetic subjects. For the mechanical tests themselves, although it is possible that some of the diabetic tissue specimens may not have undergone changes even after ~15 years of hyperglycemia exposure, this risk is low as our estimate of disease duration is conservative given that diabetes diagnosis may occur 9–12 years after onset (Harris et al.). A general limitation of this data was the large inter-specimen variability, especially for the stress relaxation response.

This study demonstrates that changes occur in the shear mechanical properties of the plantar soft tissue with diabetes, most notably making it stiffer and thereby compromising its ability to dissipate the stresses borne by the foot that may increase ulceration risk. These results have potential implications for the diabetic foot and plantar ulcer prevention if used in

tandem with computational foot models, for example, to investigate orthotic shear stress reduction devices.

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References

- Arbogast KB, Margulies SS. Material characterization of the brainstem from oscillatory shear tests. *J Biomech.* 1998; 31:801–807. [PubMed: 9802780]
- Bates D, Maechler M. lme4: Linear mixed-effects models using Eigen and Eigen. 2010
- Bilston LE, Liu Z, Phan-Thien N. Linear viscoelastic properties of bovine brain tissue in shear. *Biorheology.* 1997; 34:377–385. [PubMed: 9640354]
- Carew EO, Talman EA, Boughner DR, Vesely I. Quasi-Linear Viscoelastic theory applied to internal shearing of porcine aortic valve leaflets. *J Biomech Eng.* 1999; 121:386–392. [PubMed: 10464692]
- CDCP. National diabetes fact sheet: national estimates and general information on diabetes and prediabetes in the United States. Atlanta, GA. U.S.: Department of Health and Human Services, Centers for Disease Control and Prevention; 2011.
- Chan RW, Rodriguez ML. A simple-shear rheometer for linear viscoelastic characterization of vocal fold tissues at phonatory frequencies. *J Acoust Soc Am.* 2008; 124:1207–1219. [PubMed: 18681608]
- Cheung YY, Dooley M, Miller TB, Kennedy F, Lynch F Jr, Wrobel JS, Paulson K, Weaver J. Magnetic resonance elastography of the plantar fat pads: Preliminary study in diabetic patients and asymptomatic volunteers. *Journal of Computer Assisted Tomography.* 2006; 30:321–326. [PubMed: 16628057]
- Darvish KK, Crandall JR. Nonlinear viscoelastic effects in oscillatory shear deformation of brain tissue. *Med Eng Phys.* 2001; 23:633–645. [PubMed: 11755808]
- Gefen A, Megido-Ravid M, Azariah M, Itzhak Y, Arcan M. Integration of plantar soft tissue stiffness measurements in routine MRI of the diabetic foot. *Clinical Biomechanics.* 2001; 16:921–925. [PubMed: 11733132]
- Harris MI, Klein R, Welborn TA, Knudman MW. Onset of NIDDM occurs at least 4–7 yr before clinical diagnosis. *Diabetes Care.* 1992; 15:815–819. [PubMed: 1516497]
- Hayes WC, Bodine AJ. Flow-independent viscoelastic properties of articular cartilage matrix. *J Biomech.* 1978; 11:407–419. [PubMed: 213441]
- Holt B, Tripathi A, Morgan J. Viscoelastic response of human skin to low magnitude physiologically relevant shear. *J Biomech.* 2008; 41:2689–2695. [PubMed: 18672246]
- Horgan CO, Ogden RW, Saccomandi G. A theory of stress softening of elastomers based on finite chain extensibility. *Proceedings of the Royal Society : Mathematical, Physical, and Engineering Sciences.* 2004; 460:1737–1754.
- Hosein R, Lord M. A study of in-shoe plantar shear in normals. *Clin Biomech (Bristol Avon).* 2000; 15:46–53.
- Hsu CC, Tsai WC, Hsiao TY, Tseng FY, Shau YW, Wang CL, Lin SC. Diabetic effects on microchambers and macrochambers tissue properties in human heel pads. *Clin Biomech (Bristol Avon).* 2009; 24:682–686.
- Hsu CC, Tsai WC, Shau YW, Lee KL, Hu CF. Altered energy dissipation ratio of the plantar soft tissues under the metatarsal heads in patients with type 2 diabetes mellitus: a pilot study. *Clin Biomech (Bristol Avon).* 2007; 22:67–73.
- Hsu TC, Lee YS, Shau YW. Biomechanics of the heel pad for type 2 diabetic patients. *Clin Biomech (Bristol Avon).* 2002; 17:291–296.
- Hsu TC, Wang CL, Shau YW, Tang FT, Li KL, Chen CY. Altered heel-pad mechanical properties in patients with Type 2 diabetes mellitus. *Diabet Med.* 2000; 17:854–859. [PubMed: 11168328]

- Iatridis JC, Kumar S, Foster RJ, Weidenbaum M, Mow VC. Shear mechanical properties of human lumbar annulus fibrosus. *J Orthop Res*. 1999; 17:732–737. [PubMed: 10569484]
- Iatridis JC, Setton LA, Weidenbaum M, Mow VC. The viscoelastic behavior of the non-degenerate human lumbar nucleus pulposus in shear. *J Biomech*. 1997; 30:1005–1013. [PubMed: 9391867]
- Klaesner JW, Hastings MK, Zou D, Lewis C, Mueller MJ. Plantar tissue stiffness in patients with diabetes mellitus and peripheral neuropathy. *Arch Phys Med Rehabil*. 2002; 83:1796–1801. [PubMed: 12474190]
- Ledoux WR, Blevins JJ. The compressive material properties of the plantar soft tissue. *Journal of Biomechanics*. 2007; 40:2975–2981. [PubMed: 17433335]
- Ledoux WR, Hillstrom HJ. The distributed plantar vertical force of neutrally aligned and pes planus feet. *Gait Posture*. 2002; 15:1–9. [PubMed: 11809575]
- Liu Z, Bilston LE. Large deformation shear properties of liver tissue. *Biorheology*. 2002; 39:735–742. [PubMed: 12454439]
- Miller-Young, JE.; Duncan, NA. Material properties of the human calcaneal fat pad in compression: validation experiments; In 4th World Congress of Biomechanics; Calgary, AB. 2002.
- Pai, S. Ph.D. Dissertation. University of Washington, Seattle; 2011. Changes in the Mechanical Properties of the Plantar Soft Tissue with Diabetes.
- Pai S, Ledoux WR. The compressive mechanical properties of diabetic and non-diabetic plantar soft tissue. *Journal of Biomechanics*. 2010; 43:1754–1760. [PubMed: 20207359]
- Pai S, Ledoux WR. The quasi-linear viscoelastic properties of diabetic and non-diabetic plantar soft tissue. *Annals of Biomedical Engineering*. 2011; 39:1517–1527. [PubMed: 21327701]
- Piaggese A, Romanelli M, Schipani E, Campi F, Magliaro A, Baccetti F, Navalesi R. Hardness of plantar skin in diabetic neuropathic feet. *J Diabetes Complications*. 1999; 13:129–134. [PubMed: 10509872]
- Prange MT, Margulies SS. Regional, directional, and age-dependent properties of the brain undergoing large deformation. *J Biomech Eng*. 2002; 124:244–252. [PubMed: 12002135]
- R-Development-Core-Team. R: A language and environment for statistical computing. Vienna, Austria: R Foundation for Statistical Computing; 2010.
- Shuck LZ, Advani SH. Rheological response of human brain tissue in shear. *Journal of basic engineering*. 1972; 94:905–911.
- Tanaka E, Iwabuchi Y, Rego EB, Koolstra JH, Yamano E, Hasegawa T, Kawazoe A, Kawai N, Tanne K. Dynamic shear behavior of mandibular condylar cartilage is dependent on testing direction. *J Biomech*. 2008; 41:1119–1123. [PubMed: 18242620]
- Weaver JB, Doyley M, Cheung Y, Kennedy F, Madsen EL, Van Houten EE, Paulsen K. Imaging the shear modulus of the heel fat pads. *Clin Biomech (Bristol Avon)*. 2005; 20:312–319.
- Yavuz M, Botek G, Davis BL. Plantar shear stress distributions: comparing actual and predicted frictional forces at the foot-ground interface. *J Biomech*. 2007; 40:3045–3049. [PubMed: 17449038]
- Yavuz M, Erdemir A, Botek G, Hirschman GB, Bardsley L, Davis BL. Peak plantar pressure and shear locations: relevance to diabetic patients. *Diabetes Care*. 2007; 30:2643–2645. [PubMed: 17620447]
- Yavuz M, Tajaddini A, Botek G, Davis BL. Temporal characteristics of plantar shear distribution: relevance to diabetic patients. *J Biomech*. 2008; 41:556–559. [PubMed: 18054025]
- Zheng YP, Choi YK, Wong K, Chan S, Mak AF. Biomechanical assessment of plantar foot tissue in diabetic patients using an ultrasound indentation system. *Ultrasound Med Biol*. 2000; 26:451–456. [PubMed: 10773376]
- Zou D, Mueller MJ, Lott DJ. Effect of peak pressure and pressure gradient on subsurface shear stresses in the neuropathic foot. *J Biomech*. 2007; 40:883–890. [PubMed: 16677657]

Fig. 1.

Specimen preparation with (a) specimen locations at the hallux (ha), first, third, and fifth metatarsal heads (m1, m3, m5), lateral midfoot (la), and calcaneus (ca) as well as (b) sample specimen after re-punching and with stain indicating specimen orientation and (c-d) during use of custom guillotine device to ensure uniform thickness.

Fig. 2. Shear test preparation showing (a) close-up of specimen in environmental chamber after adhering to bottom platen using sandpaper and cyanoacrylate, (b) side profile of specimen after lowering top platen and (c) then sealing chamber and pumping moist warm air into the testing chamber to maintain *in vivo* conditions of near 100% humidity and ~35°C.

Fig. 3.

Sample nonlinear shear stress-strain response for all locations in one foot at both (a) 50% shear strain and (b) 85% shear strain showing S-shaped curve due to initial stiff region at low strains up to first inflection point followed by toe region up to second inflection point and then a rapid increase in stiffness at higher strains. Comparison of curves in one specimen (c) at both strain levels indicates some stress softening. Note: ha = hallux; m1, m3, and m5 = first, third, and fifth metatarsals; la = lateral midfoot; and ca = calcaneus.

Fig. 4.

Sample triangle wave data for one specimen (non-diabetic from calcaneus at 50% shear strain level) showing (a) relaxation of statically applied compressive load (negative since in compression) between the first and last cycles and (b) close-up of the 11th, 12th, and 13th triangle waves highlighting variations in compressive and shear loads with each shear displacement cycle.

Fig. 5. Normalized stress versus (a) time and (b) log time plots comparing average shear relaxation data for diabetic (D) and non-diabetic (N) specimens.

Fig. 6. Normalized stress versus (a) time and (b) log time plots comparing average relaxation data for all plantar locations where ha = hallux; m1, m3, and m5 = first, third, and fifth metatarsals; la = lateral midfoot; and ca = calcaneus (note that standard deviations are shown in Fig. 7).

Fig. 7.

Normalized stress versus time plots showing average relaxation data and standard deviations for individual plantar locations where ha = hallux; m1, m3, and m5 = first, third, and fifth metatarsals; la = lateral midfoot; and ca = calcaneus.

Table 1

Mean [standard error] donor information

	Diabetic	Non-diabetic	p [*]
Age (yrs)	71 [7]	67 [4]	0.4
Weight (kg)	94 [25]	76 [11]	0.2
Gender (M:F)	2:2	3:2	-
Diabetes duration (years)	20.3 [8.1]	-	-

* p<0.05 for two-sample t-test (1 measurement per foot; n = 4 for diabetic feet, n = 5 for non-diabetic feet)

Table 2

Mean [standard error] specimen parameters by disease status

	Diabetic	Non-diabetic	p*
Specimen weight (g)	0.383 [0.012]	0.381 [0.007]	0.9
Initial thickness (mm)	3.32 [0.08]	3.26 [0.06]	0.6
Compressed thickness (mm)	2.05 [0.05]	2.09 [0.05]	0.6
Compressive strain (mm/mm)	0.382 [0.010]	0.359 [0.008]	0.13

* p<0.05 indicates significance using linear mixed effects models of specimen parameter on disease status with random effect for foot (one measurement per foot/location; 24 measures in 24 specimens for four diabetic feet, 30 measures in 30 specimens for five non-diabetic feet)

Table 3

Mean [standard error] elastic parameters by disease status

	Diabetic	Non-diabetic	p*
Peak compressive stress (kPa)	86.7 [9.4]	60.2 [8.4]	0.063
Base compressive stress (kPa)	67.6 [10.3]	46.3 [9.2]	0.10
Shear strain angle (°)	46.6 [2.7]	45.6 [2.5]	0.085
Peak shear stress (kPa)	23.9 [3.0]	15.7 [2.6]	0.037
Initial shear modulus (kPa)	143 [24]	103 [21]	0.2
Toe shear modulus (kPa)	20.0 [2.7]	12.3 [2.4]	0.036
Final shear modulus (kPa)	59.7 [6.9]	40.6 [6.2]	0.038
Energy loss (%)	46.3 [1.4]	43.8 [1.2]	0.14

* p<0.05 indicates significance using linear mixed effects models of elastic parameter on disease status with strain group and location as covariates and multiple random effects (144 measures in 24 specimens for four diabetic feet, 180 measures in 30 specimens for five non-diabetic feet). Note that SEs were obtained from linear mixed effect models on disease status with foot as a random variable.

Table 4

Mean [standard error] specimen parameters by location

	ha	m1	m3	m5	la	ca
Specimen weight (g)	0.39	0.40	0.36	0.41	0.37	0.36
Initial thickness (mm)	3.3 [0.4]	3.5 [0.4]	3.2 [0.3]	3.5 [0.3]	3.2 [0.2]	3.1 [0.3]
Compressed thickness (mm)	2.2 [0.2]	2.1 [0.3]	2.1 [0.3]	2.2 [0.3]	2.0 [0.1]	2.0 [0.2]
Compressive strain (mm/mm)	0.34	0.40	0.37	0.36	0.38	0.36

Note: No overall significant differences were found using linear mixed effects models of elastic parameter on plantar location with strain group and disease status as covariates and multiple random effects (54 measures in 54 specimens and nine feet), ha = hallux; m1, m3, and m5 = first, third, and fifth metatarsals; la = lateral midfoot; and ca = calcaneus

Table 5

Mean [standard error] elastic parameters by location

	ha	m1	m3	m5	la	ca
Peak compressive stress	68.7 [5.6]	74.1 [9.0]	85.6 [12.8]	65.4 [9.2]	59.0 [8.6]	79.0 [9.2]
Base compressive stress	56.3 [9.2]	65.0 [10.4]	61.1 [12.5]	54.5 [9.2]	46.2 [7.0]	51.4 [5.8]
Shear strain angle (°)	44.9 [2.4]	47.3 [0.8]	46.0 [0.8]	45.7 [3.3]	46.6 [0.6]	45.6 [0.6]
Peak shear stress (kPa)	16.3 [1.5]	18.6 [4.7]	23.0 [3.4]	16.7 [3.1]	18.1 [3.4]	23.6 [3.9]
Initial shear modulus (kPa)	110 [15]	140 [37]	122 [20]	120 [24]	107 [19]	124 [18]
Toe shear modulus (kPa)	12.9 [1.3]	16.3 [3.8]	19.3 [3.7]	13.8 [2.8]	14.1 [2.7]	17.8 [2.8]
Final shear modulus (kPa)	39.9 [5.1]	34.7 [9.8]	61.0 [8.3]	36.6 [8.4]	50.5 [10.7]	71.8 [15.9]
Energy loss (%)	41.0 [2.7]	47.7 [1.7]	41.5 [2.0]	45.5 [2.7]	44.6 [1.3]	49.2 [2.2]

Note: No overall significant differences were found using linear mixed effects models of elastic parameter on plantar location with strain group and disease status as covariates and multiple random effects (324 measures in 54 specimens and nine feet); ha = hallux; m1, m3, and m5 = first, third, and fifth metatarsals; la = lateral midfoot; and ca = calcaneus

Table 6

Mean [standard error] viscoelastic parameters by disease status

	Diabetic	Non-diabetic	p [*]
Peak compressive stress	149.2 [9.5]	106.6 [6.3]	0.010
Ramp time (s)	0.253 [0.0004]	0.252 [0.0008]	0.3
Peak shear stress (kPa)	28.5 [4.1]	17.6 [2.0]	0.032
Initial slope (kPa/s)	−140 [19]	−101 [10]	0.10
Middle slope (kPa/s)	−0.152 [0.022]	−0.091 [0.012]	0.021
End slope (kPa/s)	−0.0009 [0.0013]	−0.0028 [0.0010]	0.2
Normalized area (N.s/N)	50.3 [5.9]	41.0 [3.3]	0.2

* p<0.05 indicates significance using linear mixed effects regression on relaxation parameter (dependent variable) by disease status (independent fixed effect) adjusting for location with random effect for foot (1 measurement per foot/location; 24 measures in 24 specimens and four feet for diabetic donors, 30 measures in 30 specimens, 5 feet for non-diabetic donors)

Table 7

Mean [standard error] viscoelastic parameters by location

	ha	m1	m3	m5	la	ca	p*
Peak compressive stress (kPa)	11.5 [1.2]	120 [11]	156 [18]	118 [16]	101 [13]	144 [18]	0.016 ⁺
Ramp time (s)	0.254 [0.0002]	0.250 [0.0024]	0.253 [0.0007]	0.252 [0.0008]	0.252 [0.0005]	0.252 [0.0006]	0.2
Peak shear stress (kPa)	16.4 [1.6]	18.1 [6.0]	30.0 [4.6]	15.5 [4.3]	23.1 [6.5]	31.7 [6.8]	0.052
Initial slope (kPa/s)	-86 [7]	-107 [31]	-144 [20]	-82 [18]	-129 [29]	-163 [31]	0.054
Middle slope (kPa/s)	-0.098 [0.012]	-0.080 [0.028]	-0.178 [0.032]	-0.080 [0.028]	-0.107 [0.028]	-0.164 [0.038]	0.025
End slope (kPa/s)	-0.0015 [0.0017]	-0.0034 [0.0019]	-0.0030 [0.0019]	-0.0007 [0.0022]	-0.0003 [0.0021]	-0.0028 [0.0023]	0.8
Normalized area (N.s/N)	48.0 [5.9]	34.8 [8.3]	50.5 [6.5]	32.0 [11]	51.3 [7.4]	54.2 [6.5]	0.2

* p<0.05 indicates overall significance using linear mixed effects regression on relaxation parameter (dependent variable) by location (independent fixed effect) adjusting for disease status with random effect for foot (54 measurements for 9 feet).

⁺ Post-hoc analysis yielded significant difference between LA and M3 (p<0.0036 using Bonferroni's correction for multiple testing), ha = hallux; m1, m3, and m5 = first, third, and fifth metatarsals; la = lateral midfoot; and ca = calcaneus