Published in final edited form as:
J Biomech. 2012 February 2; 45(3): 619–622. doi:10.1016/j.jbiomech.2011.11.004.

Spatial relationships between shearing stresses and pressure on the plantar skin surface during gait

Samantha Stucke[1], **Daniel McFarland**[1], **Larry Goss, PhD**[2], **Sergey Fonov, PhD**[2], **Grant R. McMillan, PhD**[2], **Amy Tucker, MD**[4], **Necip Berme, PhD**[3], **Hasan Cenk Guler, PhD**[3], **Chris Bigelow**[3], and **Brian L. Davis, PhD**[1,*]

[1]Medical Device Development Center, Austen BioInnovation Institute in Akron, Akron, OH 44308, USA

[2]Innovative Scientific Solutions Inc., Dayton, OH 45440, USA

[3]Bertec Corporation, Columbus, OH 43229, USA

[4]Akron General Medical Center, Akron, OH 44307, USA

Abstract

Based on the hypothesis that diabetic foot lesions have a mechanical etiology, extensive efforts have sought to establish a relationship between ulcer occurrence and plantar pressure distribution. However, these factors are still not fully understood. The purpose of this study was to simultaneously record shear and pressure distributions in the heel and forefoot and to answer whether: (i) peak pressure and peak shear for anterior-posterior (AP) and medio-lateral (ML) occur at different locations, and if (ii) peak pressure is always centrally located between sites of maximum AP and ML shear stresses. A custom built system was used to collect shear and pressure data simultaneously on 11 subjects using the 2-step method. The peak pressure was found to be 362 kPa ±106 in the heel and 527 kPa ± 123 in the forefoot. In addition, the average peak shear values were higher in the forefoot than in the heel. The greatest shear on the plantar surface of the forefoot occurred in the anterior direction (mean and std dev: 37.7 ±7.6 kPa), whereas for the heel, peak shear on the foot was in the posterior direction (21.2 ±5 kPa). The results of this study suggest that the interactions of the shear forces caused greater "spreading" in the forefoot and greater tissue "dragging" in the heel. The results also showed that peak shear stresses do not occur at the same site or time as peak pressure. This may be an important factor in locating where skin breakdown occurs in patients at high-risk for ulceration.

Keywords

Biomechanics; Bioinstrumentation; Diabetic; Plantarsurface; Ulceration

---

*Corresponding Author; Brian L. Davis, Ph.D. Vice President, Director, Medical Device Development Center Austen BioInnovation Institute in Akron 1 South Main Street, Suite 401 Tel: (330) 572-7547 Fax: (330) 379-1192 bdavis@abiakron.org.

Conflict of interest statement
ABIA does not have conflict of interest whereas the technology used in this paper was developed by Bertec and ISSI and commercialization of this system will benefit Bertec and ISSI.

1.Introduction

Diabetic foot ulcers continue to be a burden on the US healthcare system with an annual cost of approximately $6 billion (Frykberg et al. 2006). Based on the hypothesis that diabetic foot lesions have a mechanical etiology, extensive efforts have sought to establish a relationship between ulcer occurrence and plantar pressure distribution. In most of the pressure distribution studies peak pressure parameters were chosen as a possible ulcer predictor. However the existing longitudinal studies have yielded only moderate correlations between peak pressure and the occurrence of diabetic foot lesions (Armstrong et al. 1998, Lavery et al. 2003, Veves et al. 1992).

Surprisingly, only one research group has examined whether all plantar ulcers developed in the follow-up period matched the baseline peak pressure sites. Veves et al. (1992) reported that only 38% of the ulcers developed under the peak pressure area. As an outcome, foot pressure has been labeled as a “poor tool” in the prediction of diabetic ulcers and where they would occur (Lavery et al. 2003).

Recently, investigators have examined shear stresses and their distribution under diabetic feet in more detail. One such study (Yavuz et al. 2007) showed that shearing stresses and peak pressures do not typically occur at the same location. What has not been studied is whether this discrepancy between peak shear locations is due to tissue being “spread” radially as a result of pressure between the foot and ground, or whether it is due to a “dragging” effect where the forward (or backward) motion of the foot causes tissue to become bunched in front of (or behind) the site of maximum pressure. Therefore the purpose of this study was to simultaneously record shear and pressure distributions in the heel and forefoot and answer the questions whether: (i) peak pressure and peak shear for anterior-posterior (AP) and medio-lateral (ML) occur at different locations, and if (ii) peak pressure is always centrally located between sites of maximum AP and ML shear stresses. Answers to these questions would shed light on the complex spatial and temporal interactions between shear and pressure acting on the plantar surface of the foot.

2.Research Design and Methods

Shear and Pressure data during walking were collected on 11 volunteers (7Males/4Females, mean age 38 ± 14.5 years), none of whom had (i) gross foot deformities (minor clawing of the toes was permissible), (ii) prior foot surgeries nor (iii) foot pain. The protocol was explained to the volunteers before their participation and each signed an informed consent form which was approved by the Institutional Review Board. Detailed patient characteristics are given in Table 1.

The custom built shear and pressure system consists of a reusable 40×58×0.17 cm surface stress sensitive film (S3F) (Fonov et al. 2005, 2007) sensitive to pressure and shear mounted on a 60×60 cm 6-component force plate that can obtain ground reaction forces (Figure 1a). The device was mounted in an 8’ × 2’ walkway in such a manner that the top of the stress sensitive film was flush with the surrounding walking surface (Figure 1b). Shear and pressure data were collected on the left foot, using the 2-step method (McPoil et al. 1999). Subjects initiated walking with the right foot and took a series of 3 steps; data were collected from the subjects’ 2nd step. Three bare foot trials were collected for each subject.

The output of the device consisted of three data vectors; vertical, AP and ML shear forces. The process of measuring pressure and shear stress is accomplished in three steps. First, the normal and tangential displacements of the film are optically measured. These displacements are then converted to pressure and shear stress distributions using a physical stress-strain model of the film. Finally the force plate measurements are used to validate and, if necessary, rescale the pressure and shear stress distributions. Note that anterior, posterior, medial and lateral shear acting on the foot, are designated as S_{ant}, S_{pos}, S_{med} and S_{lat}, respectively. The Cartesian coordinates for the locations of the peak stresses occurring in the forefoot and heel were determined for each dataset. Difference in peak pressure and shear location errors were quantified by calculating Euclidian distances (D) between peak stresses.

3. Results

The mean peak pressure values in the heel and forefoot were found to be 362 ±106 kPa and 527 ± 123 kPa respectively, which corresponds well with previous studies (Cavanagh et al. 1987). Mean peak shear values in the forefoot were higher than in the heel. The peak average shear acting on the plantar surface of the forefoot was directed anteriorly (37.7 ±7.6 kPa) whereas the minimum average shear was in the posterior direction (17.6 ±5.7 kPa). For the heel the peak average shear acting on the plantar surface occurred in the posterior direction (21.2 ±5 kPa) and the minimum average shear in the anterior direction (8.3 ±2.8 kPa) (Figure 2a).

In all 11 subjects peak pressure and peak shear for AP and ML occurred at different locations in the heel and forefoot. In the heel, the peak pressure site, on average, was 24.8mm away from S_{ant}, 17.37mm from S_{pos}, 20.93mm from S_{med} and 22.94mm from S_{lat}. In the forefoot, the peak pressure site, on average, was located 22.79mm away from S_{ant}, 29.66 mm from S_{pos}, 24.26 mm from S_{med} and 26.67mm from S_{lat}, (Figure 2b). In addition the peak AP shear values not only occurred at different locations than the peak pressure values, but also at different times. In the heel, the peak AP shear values occurred prior to the peak pressure value 60.61% of the time, while in the forefoot, it occurred afterwards 57.58% of the time (Figures 3a and b).

The corresponding shear forces acting in the immediate vicinity of the peak pressure location were examined. The number of occasions when there were outwardly directed forces on either side of the peak pressure location was tabulated; this number of occurrences indicated a "spreading" effect. Conversely, the number of times shearing stresses were unidirectional and were before or after the peak pressure location, indicated situations where "dragging" occurred (Figures 4a and b). This data showed that in the forefoot shear forces tended to cause tissue to have a "spreading" effect. However under the heel the AP shear forces created a "dragging" effect. Overall, "spreading" occurred in both directions in the forefoot (94% ML, 67% AP). In the heel region "spreading" occurred 82% of the time in the ML direction, while "dragging" occurred in 82% of the time in the AP direction.

4. Discussion

This study focused on both the magnitudes of 3D skin stresses acting on the plantar surface of the foot and whether pressure was more likely to be associated with radial "spreading" shear stresses or traction that is due to skin "dragging" at the interface between foot and ground. These results are important as the occurrences of skin breakdown are much higher in the forefoot then in the heel (Caselli et al. 2002) and the higher shear values might help explain why skin breakdown occurs more in the forefoot than in the heel (Mueller et al. 2005).

In addition, it is important to note that the peak shear values were always at different locations than the peak pressure values. This might help explain why foot pressure alone is a poor predictor of ulceration (Lavery et al. 2003). The results of this study also suggest that peak shear values not only occur at different locations than peak pressure, but also at different times, which also corresponds well with previous studies (Perry et al. 2002).

As expected, the maximum AP shears experienced by the heel and the forefoot are in opposite directions, which is most likely caused by the heel strike and push-off. We have shown that the interactions of the shear forces caused greater “spreading” in the forefoot (Figure 4a) and greater “dragging” in the heel. The peak shear values in the ML direction straddle the peak pressure location 94% of the time. This also occurs in the AP direction 67% of the time. Since the peak pressure is located directly in between both of the peak shear values and the forces are moving in opposite directions about the peak pressure location radial “spreading” occurs. The heel however, is subject to a “dragging” effect in the AP direction (Figure 4b). Similar to the forefoot, the peak shear values in the ML direction straddle the peak pressure location 82% of the time. However, the peak shear values in the AP direction occur prior to the peak pressure location and in the same direction (anterior to posterior) 82% of the time producing a “dragging” effect, which occurs during heel strike. These findings give us a more complete look at the stresses acting on the plantar foot.

In conclusion, the results of this study show that peak shear stresses do not occur at the same site or time as peak pressure and that shear stress may be an important factor in locating where skin break down may occur on the plantar foot. Shear stresses are higher in the forefoot where skin breakdown is most prevalent, compared to the heel. The ability to locate peak shear and pressure on the plantar foot furthers our understanding of the factors that play a role in skin breakdown.

Acknowledgments

The authors would like to acknowledge the Wound Care Center at Akron General Medical Center for their assistance in subject recruitment.

This research was possible due to support from National Institutes of Health (Grant # 4R44DK084844-02), awarded to Bertec Corporation with Cenk Guler as the Principal Investigator. The authors are indebted to the substantial contributions by Cenk. While his untimely death has certainly affected the pace of the project, his significant role in developing new biomechanical technologies will continue to serve as an inspiration to the rest of the team. Moreover, his legacy will continue by way of all the students he impacted through his teachings of biomechanics, dynamics, and gait analysis.

References

Akhlaghi F, Pepper MG. In-shoe biaxial shear force measurement: the Kent shear system. Medical and Biological Engineering and Computing. 1996; 34(4):315–317. [PubMed: 8935501]

Armstrong DG, Peters EJ, Athanasiou KA, Lavery LA. Is there a critical level of plantar foot pressure to identify patients at risk for neuropathic foot ulceration? Journal of Foot and Ankle Surgery. 1998; 37(4):303–7. [PubMed: 9710782]

Brand PW. Tenderizing the foot. Foot Ankle Int. 2003; 24(6):457–61. [PubMed: 12854665]

Bus SA, Yang QX, Wang JH, Smith MB, Wunderlich R, Cavanagh PR. Intrinsic muscle atrophy and toe deformity in the diabetic neuropathic foot: a magnetic resonance imaging study. Diabetes Care. 2002; 25(8):1444–50. [PubMed: 12145248]

Caselli A, Pham H, Giurini JM, Armstrong DG, Veves A. The forefoot-to-rearfoot plantar pressure ratio is increased in severe diabetic neuropathy and can predict foot ulceration. Diabetes Care. 2002; 25(6):1066–1071. [PubMed: 12032116]

Cavanagh P, Rodgers M, Iiboshi A. Pressure distribution under symptom-free feet during barefoot standing. Foot & Ankle. 1987; 7(5):262–276. [PubMed: 3583160]

Chen W, Tang F, Ju C. Stress distribution of the foot during mid-stance to push-off in barefoot gait: a 3D finite element analysis. Clinical Biomechanics. 2001; 16:614–620. [PubMed: 11470304]

Davis BL. Foot ulceration: hypotheses concerning shear and vertical forces acting on adjacent regions of skin. Med Hypotheses. 1993; 40(1):44–7. [PubMed: 8455466]

Fonov SD, Goss LP, Jones EG, Crafton JW, Fonov VS. Identification of pressure measuring system based on surface stress sensitive films and pressure sensitive paints. Instrumentation in Aerospace Simulation Facilities. 2005:123–127.

Fonov SD, Jones EG, Crafton JW, Goss LP. Using surface stress sensitive films for pressure and friction measurements in mini- and micro channels. Instrumentation in Aerospace Simulation Facilities. 2007:1–7.

Frykberg RG, Zgonis T, Armstrong DG, Driver VR, Giurini JM, Kravitz SR, Landsman AS, Lavery LA, Moore JC, Schuberth JM, Wukich DK, Andersen C, Vanore JV. Diabetic foot disorders: a clinical practice guideline (2006 revision). Journal of Foot and Ankle Surgery. 2006; 45(5 Suppl):S1–S66. [PubMed: 17280936]

Giacomozzi C, Macellari V. Piezo-dynamometric platform for a more complete analysis of foot-to-floor interaction. IEEE Transactions on Rehabilitation Engineering. 1997; 5(4):322–30. [PubMed: 9422457]

Lavery LA, Armstrong DG, Wunderlich RP, Tredwell J, Boulton AJ. Predictive value of foot pressure assessment as part of a population-based diabetes disease management program. Diabetes Care. 2003; 26(4):1069–73. [PubMed: 12663575]

Lord M, Hosein R. A study of in-shoe plantar shear in patients with diabetic neuropathy. Clinical Biomechanics (Bristol, Avon). 2000; 15(4):278–83.

Lott DJ, Zou D, Mueller MJ. Pressure gradient and subsurface shear stress on the neuropathic forefoot. Clinical Biomechanics. 2008; 23:342–348. [PubMed: 18060668]

Maluf KS, Mueller MJ. Comparison of physical activity and cumulative plantar tissue stress among subjects with and without diabetes mellitus and a history of recurrent plantar ulcers. Clinical Biomechanics. 2003; 18:567–575. [PubMed: 12880704]

McPoil TG, Cornwall MW, Dupuis L, Cornwell M. Variability of plantar pressure data. A comparison of the two-step and midgait methods. Journal of the American Podiatric Medicine Association. 1999; 89(10):495–501.

Mueller MJ, Minor SD, Diamond JE, Blair VP. Relationship of foot deformity to ulcer location in patients with diabetes mellitus. Physical Therapy. 1990; 70(6):356–362. [PubMed: 2345779]

Mueller MJ, Zou D, Lott DJ. "Pressure gradient" as an indicator of plantar skin injury. Diabetes Care. 2005; 28:2908–2912. [PubMed: 16306553]

Murray HJ, Young MJ, Hollis S, Boulton AJM. The association between callus formation, high pressures and neuropathy in diabetic foot ulceration. Diabetic Medicine. 1996; 13:979–982. [PubMed: 8946157]

Oyibo SO, Jude EB, Tarawneh I, Nguyen HC, Armstrong DG, Harkless LB, Boulton AJ. The effects of ulcer size and site, patient's age, sex and type and duration of diabetes on the outcome of diabetic foot ulcers. Diabetic Medicine. 2001; 18(2):133–8. [PubMed: 11251677]

Pataky Z, Golay A, Faravel L, Silva JDa, Makoundou V, Peter-Riesch B, Assal JP. The impact of callosities on the magnitude and duration of plantar pressure in patients with diabetes mellitus. DiabetesMetab (Paris). 2002; 28:356–361.

Pavicic T, Korting HC. Xerosis and callus formation as a key to the diabetic foot syndrome: Dermatologic view of the problem and its management. JDDG. 2006; 4:935–941. [PubMed: 17081268]

Perry JE, Hall JO, Davis BL. Simultaneous measurement of plantar pressure and shear forces in diabetic individuals. Gait and Posture. 2002; 15:101–107. [PubMed: 11809586]

Pollard JP, Le Quesne LP. Method of healing diabetic forefoot ulcers. British Medical Journal (Clinical Research Ed.). 1983; 286(6363):436–437. [PubMed: 6401552]

Sanders JE, Greve JM, Mitchell SB, Zachariah SG. Material properties of commonly-used interface materials and their static coefficients of friction with skin and socks. J Rehabil Res Dev. 1998; 35(2):161–176. [PubMed: 9651888]

Stacpoole-Shea S, Shea G, Lavery L. An examination of plantar pressure measurements to identify the location of diabetic forefoot ulceration. The Journal of Foot & Ankle Surgery. 1999; 38(2):109–115. [PubMed: 10334697]

Thomas VJ, Patil KM, Radhakrishnan S. Three-dimensional stress analysis for the mechanics of plantar ulcers in diabetic neuropathy. Med Biol Eng Comput. 2004; 42:230–235. [PubMed: 15125154]

Van Schie CH. A review of the biomechanics of the diabetic foot. Int J Low Extrem Wounds. 2005; 4:160–170. [PubMed: 16100097]

Veves A, Murray HJ, Young MJ, Boulton AJ. The risk of foot ulceration in diabetic patients with high foot pressure: a prospective study. Diabetologia. 1992; 35(7):660–3. [PubMed: 1644245]

Viceconti M, Olsen S, Burton K. Extracting clinically relevant data from finite element simulations. Clinical Biomechanics. 2005; 20:451–454. [PubMed: 15836931]

Yavuz M, Erdemir A, Botek G, Hirschman GB, Bardsley L, Davis BL. Peak plantar pressure and shear locations. Diabetes Care. 2007; 30(10):2643–2645. [PubMed: 17620447]

Yavuz M, Ocak H, Hetherington VJ, Davis BL. Prediction of plantar shear stress distribution by artificial intelligence methods. Journal of Biomechanical Engineering. 2009; 131:(091007)1–(091007)4.

Yavuz M, Tajaddini A, Botek G, Davis BL. Temporal characteristics of plantar shear distribution: Revlevance to diabetic patients. Journal of Biomechanics. 2008; 41:556–559. [PubMed: 18054025]

Zou D, Mueller MJ, Lott DJ. Effect of peak pressure and pressure gradient on subsurface shear stresses in the neuropathic foot. Journal of Biomechanics. 2007; 40:883–890. [PubMed: 16677657]

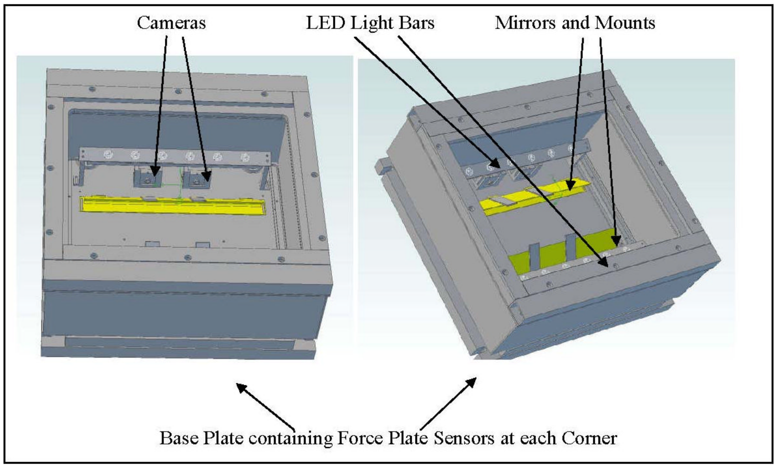

Figure 1a.
Representation of the custom built shear and pressure system. The glass plate and polymer film are removed to permit viewing of the internal components. A total of four cameras are used to image the film, although only two can be seen in these views. The mirrors direct the cameras' field of view upward to the film. The light bars provide the illumination for imaging and for excitation of the fluorescent probe in the film.

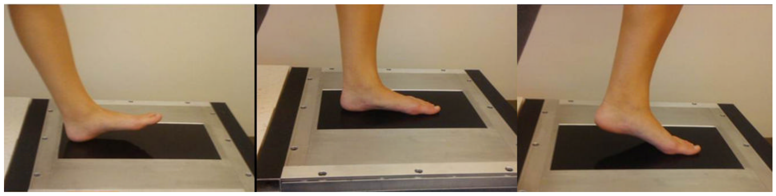

Figure 1b.
Close up view of a subject stepping on to the shear and pressure platform.

NIH-PA Author Manuscript
NIH-PA Author Manuscript

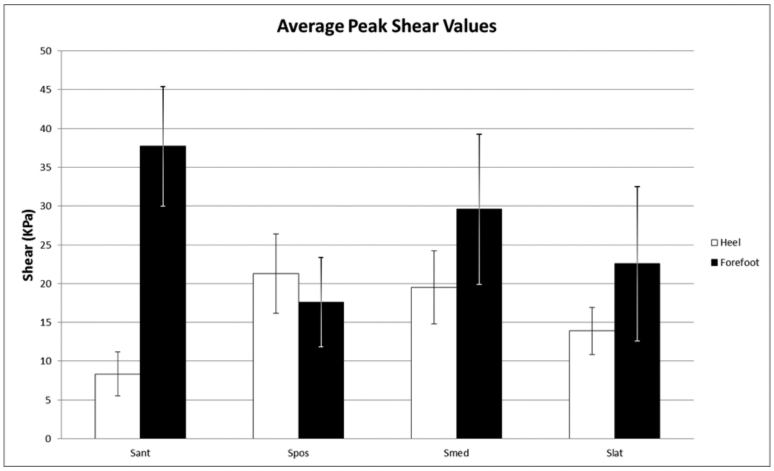

Figure 2a.
Average shear values for the heel and forefoot

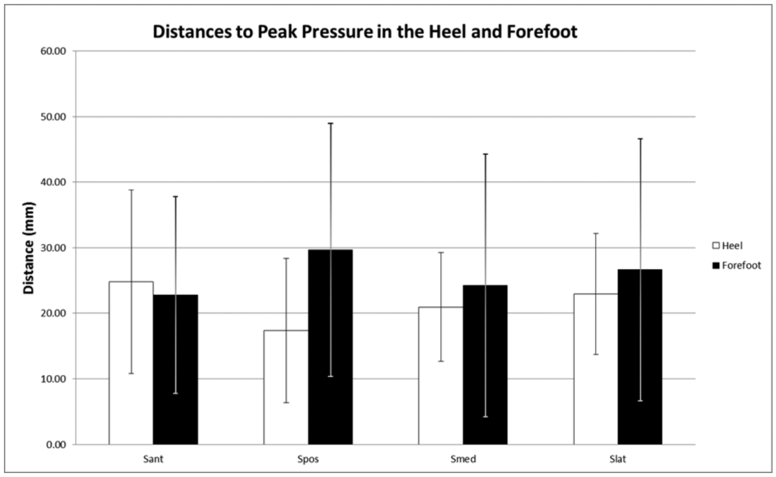

Figure 2b.
Graphic representation of the distances from average peak pressure to average shear in the Heel and Forefoot.

NIH-PA Author Manuscript
NIH-PA Author Manuscript

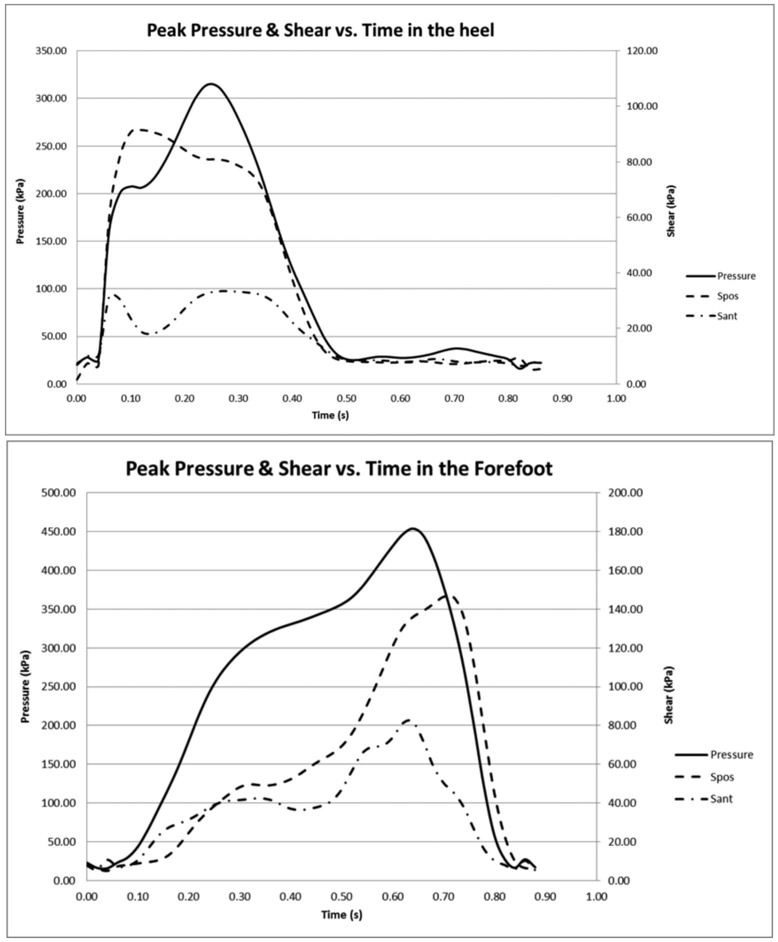

Figure 3.

Time histories for shear and pressure for a single trial for a representative subject. (a) Heel, (b) Forefoot.

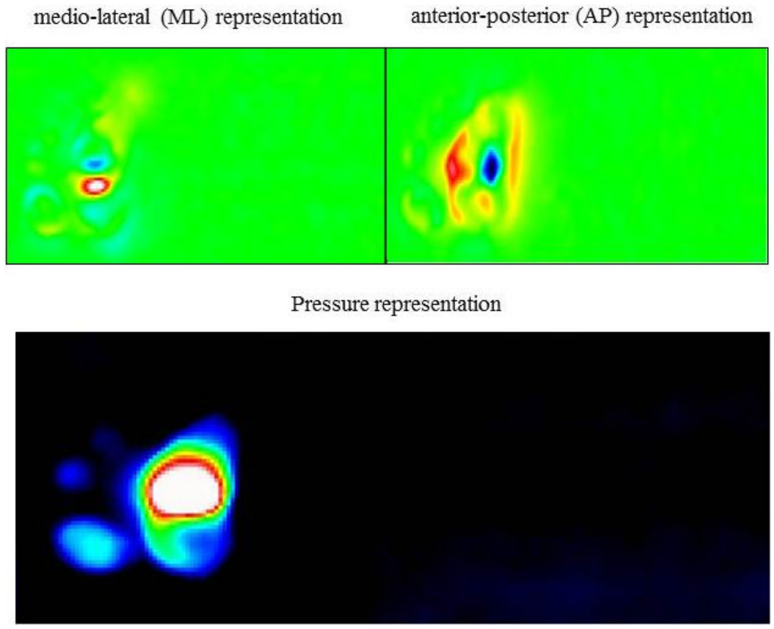

Figure 4a.
Pressure and shear locations in the forefoot of a representative subject, showing the main cause of shear in all directions is due to a radial “spreading” effect.

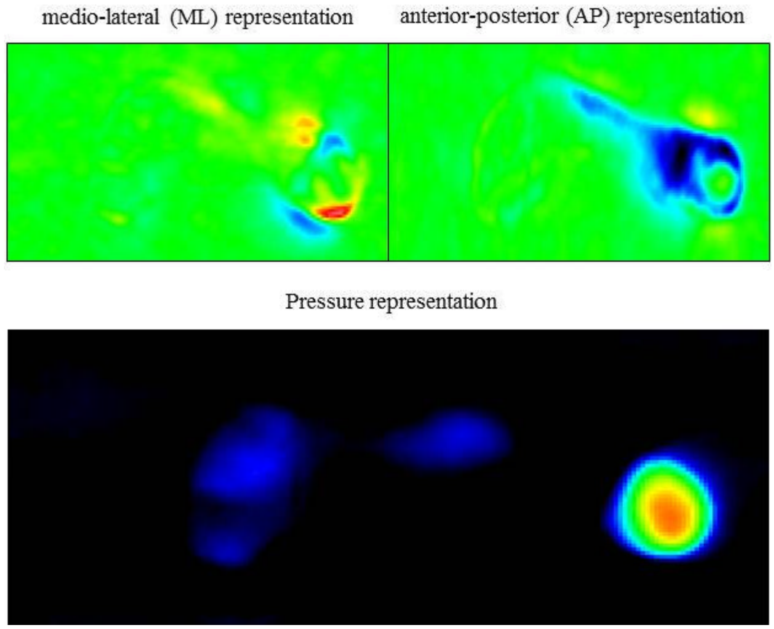

Figure 4b.
Pressure and shear locations in the heel of a representative subject, showing the main cause of shear in the AP direction is due to a “dragging” effect.

Table 1

Characteristics of the subjects

	Control
No of subjects	11
Gender	7 Male/ 4 Female
Age (years)	38 ± 14.5 (20-61)
Weight (lb.)	180 ± 23.4 (150-215)

Values are presented as the mean ± standard deviation, with the range in parentheses.