First Exploration of H-scan Ultrasound Imaging in Diabetic Foot: A Feasibility Study

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***Abstract*—Diabetic foot complications are a leading cause of morbidity and lower-limb amputation worldwide, largely driven by structural and mechanical alterations of plantar soft tissues. Reverberant shear wave ultrasound elastography has shown potential in detecting increased stiffness in diabetic plantar tissue; however, stiffness alone does not fully capture microstructural remodeling at the scatterer level. H-scan ultrasound imaging is a scatterer-size–sensitive technique that encodes frequency-dependent backscatter information into color maps, providing a novel means of assessing tissue microarchitecture. In this feasibility study, we applied H-scan imaging to the plantar soft tissues of 10 diabetic patients and 3 healthy controls. Radiofrequency ultrasound data were acquired at clinically relevant sites (1st and 3rd metatarsal heads and heel), processed using a 256-filter Gaussian convolution algorithm, and analyzed with an automated region-of-interest detection method. The intensity-weighted percentage of red pixels (IWP_{red}), representing the prevalence of larger scatterers, was extracted as a quantitative biomarker. Results showed significantly higher IWP_{red} values in participants with diabetes at the 3rd metatarsal head for both feet (left: $p \leq 0.002$, right: $p \leq 0.001$), while no significant differences were observed at the 1st metatarsal head or heel. These findings suggest that H-scan imaging can detect microstructural alterations in diabetic plantar tissues, particularly at high-risk ulceration sites. This study provides the first evidence supporting the feasibility of H-scan ultrasound as a non-invasive, rapid, and clinically deployable tool for diabetic foot risk assessment.**

***Index Terms*—H-scan ultrasound, diabetic foot, plantar soft tissue, scatterer size distribution, medical imaging, ultrasound tissue characterization, diabetic complications**

I. Introduction

Diabetic foot complications are among the most debilitating and costly sequelae of diabetes mellitus, representing a leading cause of lower-limb amputation worldwide [1]. Chronic hyperglycemia induces a cascade of metabolic and vascular changes that alter the mechanical and structural integrity of plantar soft tissues, increasing the risk of ulceration under repetitive loading [2]. Previous work has hypothesized that diabetic plantar tissues exhibit higher stiffness and altered elasticity compared to non-diabetic controls, potentially due to the accumulation of advanced glycation end-products (AGEs), increased collagen cross-linking, and microvascular compromise [3]. In particular our group employed reverberant shear wave elastography to quantify mechanical characteristics of the metatarsal heads and heel regions, reporting significant differences in tissue stiffness between diabetic and healthy subjects [4], [5].

While stiffness provides an indirect indicator of microstructural alterations, it does not directly characterize changes in acoustic scatterer properties within the tissue. Ultrasound backscatter analysis offers a complementary perspective by probing tissue microarchitecture at the sub-wavelength scale. H-scan ultrasound imaging is a scatterer-size–sensitive technique that encodes differences in scatterer morphology and distribution through a color-mapped representation, achieved via matched-filter algorithms tuned to specific scatterer dimensions [6]. This approach has proven effective in detecting pathological changes in organs such as the liver [7], [8], thyroids [9],breast [10] and kidneys [11], where fibrosis and morphological remodeling alter scatterer size distribution.

To date, H-scan imaging has not been applied to the assessment of diabetic plantar soft tissues. Given the histomorphological evidence of increased septal wall thickness and altered extracellular matrix composition in diabetic feet [12], it is plausible that these changes manifest as detectable differences in scatterer size distribution. Such differences, if measurable in vivo, could serve as a novel imaging biomarker for early detection of tissue compromise before ulceration occurs.

The objective of this study is to conduct the first exploratory application of H-scan ultrasound imaging to study the plantar soft tissues of diabetic and non-diabetic individuals, aiming to determine whether this technique can differentiate scatterer size distributions between the two groups. By establishing its feasibility in this context, H-scan could provide a non-invasive, rapid, and clinically viable tool for diabetic foot risk assessment and early intervention.

II. Theory

A. Scattering Transfer Function

Under the Born approximation for weak scattering, the echo spectrum from tissue microstructure can be written as:

$$S(f) = P(f)\, H(f), \tag{1}$$

where $P(f)$ is the transmitted pulse spectrum and $H(f)$ is the tissue-dependent transfer function. A power-law form is typically assumed:

$$H(f) \propto |f|^{\gamma}, \tag{2}$$

with γ determined by scatterer size and morphology. Small scatterers (Rayleigh regime) tend toward $\gamma \approx 2$, while larger scatterers shift the spectrum toward lower exponents. These frequency-dependent behaviors modulate the effective center frequency of the backscattered signal and form the basis for H-scan imaging [6].

B. Gaussian Filter Bank [8]

To capture these spectral shifts, H-scan imaging applies a bank of finely spaced Gaussian bandpass filters. Each filter is defined as:

$$G_i(f) = \exp\left[-\frac{(f - f_{0,i})^2}{2\sigma^2}\right], \tag{3}$$

where $f_{0,i}$ is the peak frequency of the i-th filter and σ controls the bandwidth. The set $\{f_{0,i}\}$ is distributed uniformly across the usable system bandwidth (e.g., 2.1–11.9 MHz), with sufficient overlap, ensuring that every frequency component of the RF signal is represented while maintaining narrowband selectivity.

C. 256-Convolution H-scan Algorithm [8]

The H-scan process can be formulated using a bank of $N = 256$ Gaussian bandpass functions, each centered at a fixed frequency $\{f_{0,i}\}_{i=1}^{256}$ spanning the system bandwidth. For each pixel in the image, the RF data are convolved with all 256 filters, generating a set of responses $\{c_i\}$. The maximum response is then identified as

$$i^* = \arg\max_i \, c_i, \tag{4}$$

which links the pixel to the frequency band that best represents its scattering properties.

This formulation increases the sensitivity to subtle variations in spectral content, allowing frequency-dependent scattering behaviors to be mapped with greater precision. A color representation is then constructed by assigning each pixel a value according to the index i^* of its maximum response, with higher effective frequencies (smaller scatterers) mapped toward blue and lower effective frequencies (larger scatterers) mapped toward red.

D. Attenuation Compensation [8]

To account for depth-dependent loss, attenuation correction is applied before filtering, modeled as

$$S_{\text{corr}}(f, x) = S(f)\, e^{+\alpha f x}, \tag{5}$$

where α is the attenuation coefficient and x is propagation depth. This step is usually done in deeper regions where the attenuation is a limitation; however for diabetic foot we don't have this case scenario so it can be discarded.

III. Materials and Methods

A. Study Population

Radiofrequency (RF) ultrasound data were collected from a cohort consisting of 10 diabetic patients and 3 age-matched healthy controls, following Institutional Review Board (IRB) approval. For each subject, both the left and right feet were examined, with three independent acquisitions per anatomical site. The anatomical regions of interest included the 1st and 3rd metatarsal heads (MTH) and the heel, given their clinical relevance in plantar soft tissue assessment.

B. Data Acquisition

Ultrasound imaging was performed using a Verasonics Vantage 64 LE system equipped with an L11-4v linear array transducer operating at a central frequency of 7 MHz. The transducer was coupled to the plantar surface with ultrasound gel to ensure consistent acoustic transmission. All acquisitions were conducted under standardized conditions, with subjects in a supine position and feet relaxed to minimize motion artifacts.

C. H-Scan Processing

The acquired RF signals were processed using the H-scan framework based on a 256-convolution Gaussian filter bank. Each pixel in the B-mode image was associated with the index of the Gaussian bandpass filter yielding the maximum response, enabling spectral classification of scattering sources. A color-coded map was generated by linking lower-frequency dominance (larger scatterers) to red hues and higher-frequency dominance (smaller scatterers) to blue hues.

D. Automatic ROI Detection [13]

To ensure consistency across subjects and acquisitions, an automatic region of interest (ROI) detection algorithm was applied prior to biomarker computation. The method identifies the plantar soft tissue region beneath the gel–tissue interface and above the bone boundary, reducing operator dependency and acquisition variability. Specifically, the approach relies on the lateral intensity profile of the B-mode image, followed by median filtering and adaptive thresholding to detect anatomical landmarks. The resulting rectangular ROI (illustrated as the red box in Fig. 1) enabled focusing the H-scan analysis exclusively on the tissue of interest, thereby ensuring that the quantitative biomarker extraction reflected only the relevant plantar soft tissue characteristics.

E. Quantitative Biomarker Extraction

To quantify scatterer distributions, the intensity-weighted percentage of red pixels (IWP_{red}) was computed. This metric reflects the relative prevalence of larger scatterers within the imaged tissue.

For each pixel classified as red, the corresponding B-mode intensity I_j was weighted and normalized with respect to the total intensity across the region of interest (ROI), yielding:

$$IWP_{red} = \frac{\sum_{j \in \text{red}} I_j}{\sum_{k \in ROI} I_k} \times 100\,. \tag{6}$$

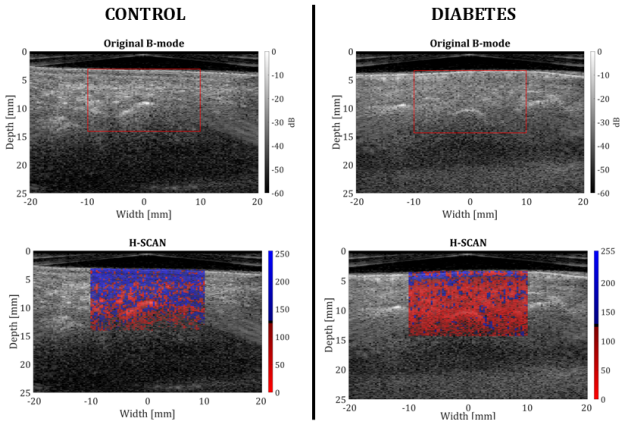

Fig. 1. Representative B-mode (top) and H-scan (bottom) images from the plantar soft tissue of a control subject (left) and a diabetic subject (right). Red rectangles indicate the automatically selected region of interest (ROI). The H-scan overlay highlights scatterer-size distribution, with blue hues denoting smaller scatterers and red hues corresponding to larger scatterers.

Here, the numerator represents the summed intensities of all red-classified pixels, while the denominator accounts for the total pixel intensity within the ROI. For each acquisition, IWP_{red} was calculated and then averaged across the three repeated measurements.

F. Statistical Analysis

Comparisons between diabetic and control groups were performed using two-sided Mann-Whitney U statistical tests at a significance threshold of $p < 0.05$ in MATLAB software. Group differences in IWP_{red} were analyzed separately for each anatomical site and laterality (right and left foot). This approach allowed the identification of localized scattering alterations associated with diabetes.

IV. Results

Representative examples of plantar soft tissue imaging are shown in Fig. 1. The H-scan overlays reveal distinct differences in scatterer-size distribution between control and diabetic subjects, with diabetic tissue exhibiting a visibly higher proportion of red-coded regions (larger scatterers) within the automatically detected ROI.

Quantitative analysis of the intensity-weighted percentage of red pixels (IWP_{red}) confirmed these observations.

TABLE I
IWP_{RED} (%) BY SITE AND GROUP

Site	Side	Control	Diabetes	p-value
1st MTH	L	51.0 ± 11.8	51.7 ± 9.1	n.s.
1st MTH	R	46.9 ± 14.7	49.2 ± 12.7	n.s.
3rd MTH	L	52.1 ± 8.6	66.9 ± 10.9	**0.002**
3rd MTH	R	51.8 ± 10.9	69.9 ± 7.6	**0.000**
Heel	L	63.0 ± 10.6	67.0 ± 11.9	n.s.
Heel	R	60.7 ± 15.0	66.2 ± 10.9	n.s.

As summarized in Table I, statistically significant group differences were found at the 3rd metatarsal head for both feet, with diabetic patients showing markedly higher IWP_{red} values (left: $p = 0.002$, right: $p = 0.000$). The corresponding boxplots in Fig. 2 illustrate the separation between groups at this site.

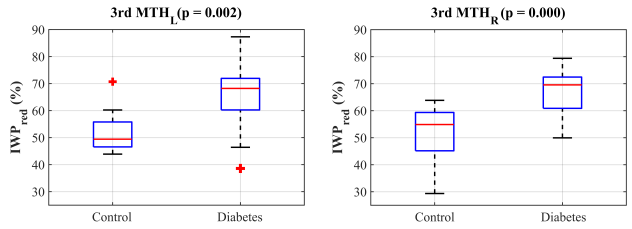

Fig. 2. Boxplots of intensity-weighted percentage of red pixels (IWP_{red}) at the 3rd metatarsal head. Significant differences between control and diabetic groups were found in both the left ($p = 0.002$) and right ($p = 0.000$) foot.

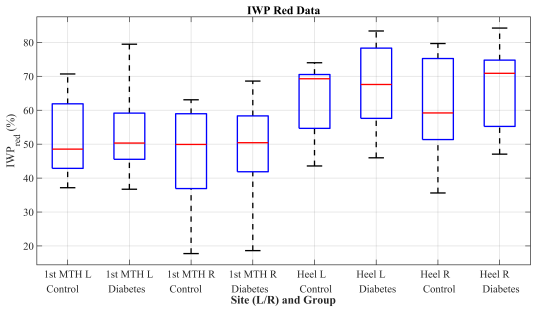

Fig. 3. Boxplots of intensity-weighted percentage of red pixels (IWP_{red}) at the 1st metatarsal head (MTH) and heel regions (left and right). No statistically significant differences were found between control and diabetic groups at these sites.

In contrast, no significant differences were observed at the 1st metatarsal head or heel regions (Fig. 3), where IWP_{red} distributions overlapped between cohorts. These results suggest that the 3rd metatarsal head may be a particularly sensitive site for detecting diabetes-related microstructural alterations using H-scan ultrasound imaging.

V. Discussion

Our study demonstrates that H-scan imaging reveals alterations in plantar tissue scatterer size distribution in diabetic subjects compared to controls, notably at the 3rd metatarsal head with significantly higher IWP_{red} values. This finding aligns with prior elastography studies that reported increased plantar tissue stiffness in diabetes, attributed to thickened collagen-rich septa and altered extracellular matrix structure in the fat pad [5].

Histomorphological analyses have shown that diabetic plantar tissue exhibits thickening and fragmentation of elastic septa, as well as increased collagen cross-linking—changes that not only stiffen the tissue but may also enlarge effective acoustic scatterers, thus shifting the H-scan spectral signature toward red hues [14]. Furthermore, mechanical displacement or atrophy of the fat pad in diabetic feet—particularly beneath the metatarsal heads—has been implicated in increased localized plantar pressure and tissue overload [15]. Such structural

and mechanical remodeling likely contributes to the elevated IWP_{red} values observed with H-scan.

Notably, no significant differences were found at the 1st metatarsal head or heel regions. This regional specificity may reflect site-dependent variations in fat pad integrity or loading patterns; the metatarsal heads bear concentrated biomechanical stress and are common loci for ulcer formation in diabetic populations [12]. Morevover, due to heel thickness attenuation can be a limiting factor in this area.

Several limitations warrant consideration. The small sample size restricts statistical power and generalizability. Additionally, while H-scan infers relative scatterer size from frequency response, it does not directly measure microstructural dimensions. Future studies combining H-scan with elastography or histological validation could enhance physiological interpretation. Longitudinal studies are also needed to assess the prognostic value of H-scan metrics in predicting ulcer development.

VI. Conclusion

In this feasibility study, H-scan ultrasound imaging effectively differentiated scatterer-size–related microstructural changes in the plantar soft tissue of diabetic individuals, particularly at the 3rd metatarsal head, where IWP_{red} was significantly elevated. These findings parallel those from elastography that reported increased plantar tissue stiffness—both interventions suggesting diabetes-induced remodeling of the plantar fat pad and collagenous septa.

H-scan thus can provide non-invasive technique for assessing diabetic foot tissue integrity. By detecting changes in acoustic scatterer distribution with anatomical specificity, this method may complement existing biomechanical assessments and contribute to early detection of the risk of diabetic foot. Further validation in larger cohorts and integration with complementary imaging modalities could pave the way for the deployment of H-scan in the clinical management of diabetic foot.

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