Quantitative Photoacoustic Feature Analysis for Vascular Monitoring in Foot Ulcers

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Introduction

- Chronic leg ulcers, a common disease associated with peripheral vascular disorders, are affecting approximately **6.5 million Americans** [1]. Patients with ulcers commonly suffer from decreased mobility and lower quality of life.
- Revascularization surgery is one of the most effective treatments for ischemia-related foot ulcers, as it restores blood flow and perfusion to the ulcer region.
- Thus, the ability to monitor the perfusion change before and after surgery is important for physicians to evaluate the success of the surgery. However, current clinical tests fail to meet this need.
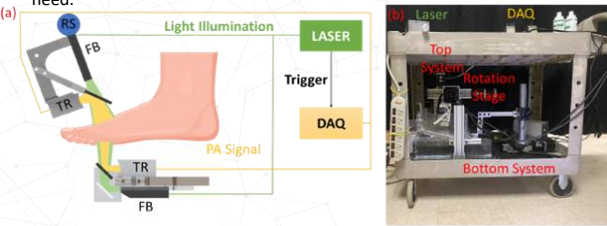

Figure 1. Experiment setups of the dual-scan imaging system. (a) A schematic drawing of the dual-scan PAT system. (b) A photograph of the system. All equipment is installed on a cart except the portable laser.

- Here, we developed a dual-scan 3D PAT system for imaging the vascular structure of the foot (Figure 1).
- The system is capable of imaging both the dorsal and plantar sides of the foot simultaneously to reduce imaging time.
- The performance of the system is demonstrated through phantom imaging and human tests. Our results indicate that the system has high potential for clinical translation.
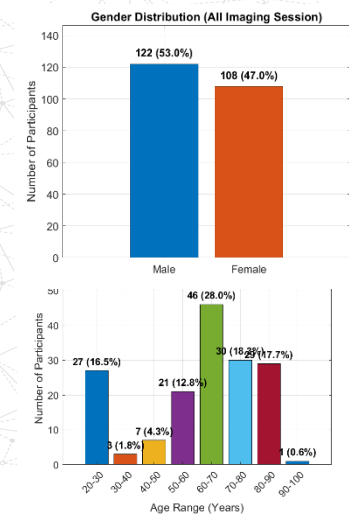
Patient Characteristics

gure 2. All Imaging Session Data (Including Volunteers Repeat Patients)

All patient Gender: 230 in total. 122 Male, 107 FemaleRace: 172 White, 6 Hispanic, 38 Asian, 13 African American Age: 27 volunteers and 164 total recorded ages (not all patients provided age information)

Unique Patient Data (Excluding Volunteers & Repeat Patients) Gender: 58 Male, 62 Female Race: 106 White, 2 Hispanic, 2 Asian, 10 African American Age: 86 unique patients with recorded age information
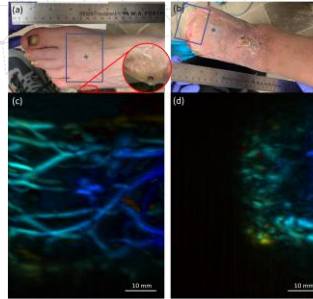
System Performance

Figure 3. Results from patient with wounds and ulcer and healthy volunteer

Patient 1 was imaged by the 1st Gen system with region of 50 mm × 86 mm.

Healthy 1 was imaged by the 2nd Gen system with region of 100mm × 86 mm.
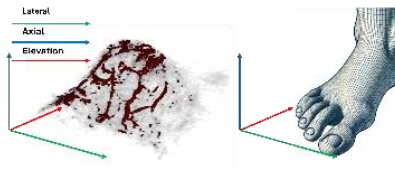
Quantitative Feature Analysis Procedure

Figure 5. Visualization for feature extraction in 3D   Figure 6. Feature extraction procedures

- Extract multiple PA image features, analyze cross-section, projection image, and 3D features. Then, Compare healthy vs. patient features and identify key indicators of ulcer healing. Provide a data-driven comparison summary.
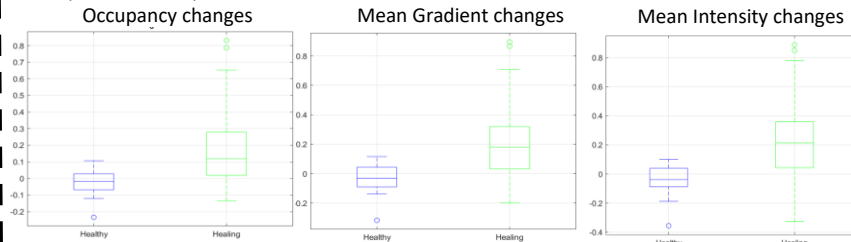

Figure 7. Single feature changes percentage comparison between healthy and patient during healing process.

- 39 features were extracted from PA images. Selected features are presented to show differences healthy, healing, and worsening patients. among
- Comparison between patient and healthy (include both patients who have completed healed and young volunteers from UB) groups reveals differences in changes linked to foot ulcer conditions.
- Key features with significant variations may serve as critical indicators of ulcer severity and healing trends.
- Limitation: Worsening cases are limited to only two patients, making it insufficient to draw definitive conclusions.
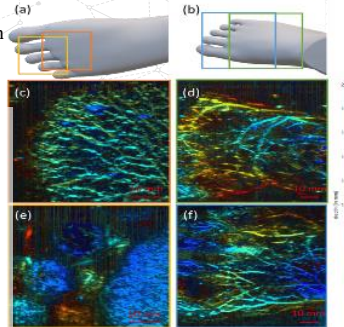
Feature (top5)	P Value
Energy_X	1.07E-5
Mean_intensity_y	2.34E-5
Energy_3D	2.40E-5
Mean_gradient_y	3.10E-5
Mid_occupancy_y	4.20E-5

SVM Model Training and Cross-Validation

Using an SVM model with **10 features** selected based on p-values, our test performance achieves around 90% accuracy in diagnosing whether a patient is healing or non-healing.
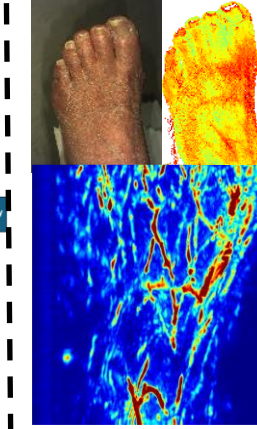
Classification Accuracy: **83.33%**

Mean Accuracy based on random test: **93.78%**
Sensitivity (TPR): 88.89% (Good at detecting healings)
False Positive Rate (FPR): 22.22% (2 non-healing misclassified)

Patient Sample Case:

Left foot 04/10/2024 visit   Left foot 05/29/2024 visit

Left foot has poor perfusion.
Surgery in 2023 (Left Femoral Endarterectomy, Stenting of the Iliac and Superficial Femoral Arteries)
Condition **worsening** over time
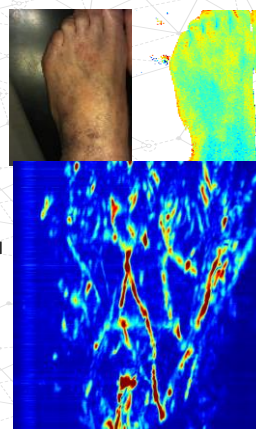
When the Condition worsening, ROI vessel features exhibit:
Mean Intensity (X) ↓ – Lower overall intensity values.
Vessel Occupancy (X) ↓ – Reduced vessel coverage in the foot.
Mean Gradient (X) ↓ – Blurred and less-defined vessel structures.
SVM model output:
worsening probability: **99.65%**

Conclusion

- PA and NIR imaging has been conducted on >100 patients. Among them, 26 patients have been imaged multiple times to track the healing process.
- 39 features were extracted, and a few have been confirmed to show higher correlation with healing.
- A model combining multiple features would show a high correlation with healing.
- Ongoing studies are conducted on analyzing the differences between two feet from the same patient.

Future work

- Patient Tracking: Monitor 5 to 10 patients before and after surgery. Currently, our data is limited to post-surgery cases only.
- Feature Analysis: Evaluate PA image features to quantify wound progression over time.
- Clinical Decision Support: Investigate whether PA imaging can help determine the post-surgery treatment.
- Validation Study: Explore PA's potential in clinical decision making.

Selected References

1. Wang, Y., et al., A portable three-dimensional photoacoustic tomography system for imaging of chronic foot ulcers. Quantitative imaging in medicine and surgery, 2019. 9(5): p. 799.
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3. Boyko, E.J., M. Monteiro-Soares, and S.G. Wheeler, Peripheral arterial disease, foot ulcers, lower extremity amputations, an diabetes. Diabetes in America. 3rd edition, 2018.

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