SkinSpex: A Portable Speckle Imaging Prototype for Multiple Skin Biomarker Detection

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***Abstract*—Laser speckle imaging is a powerful but underutilized optical technique, capable of capturing a range of physiological biomarkers, including heart rate, respiration, skin perfusion, hydration, and subtle structural changes in skin such as piloerection. Despite its proven efficacy in controlled settings, Laser speckle imaging is rarely found in wearable or point-of-care devices, which typically monitor only basic vital signs. To address this gap, we introduce SkinSpex: a compact, affordable device based on a Raspberry Pi Zero 2, integrating a multi-wavelength (560, 750, and 930 nm) laser system for flexible, non-contact speckle imaging. SkinSpex enables mapping of both hemodynamic and topographical skin features from a distance of just 10 cm, opening the door to multi-biomarker monitoring in everyday environments. Such comprehensive monitoring is especially relevant for detecting acute physiological states, including the sudden onset of opioid withdrawal, where changes in heart rate, breathing, and skin structure may occur simultaneously but are often missed by conventional wearables. By directly capturing both surface and subsurface skin dynamics, SkinSpex can provide a more complete view of physiological state, enabling earlier and more reliable detection of significant events. Our results show the unique capabilities of this compact prototype and suggest that SkinSpex could enable a new generation of wearable platforms for continuous, comprehensive health assessment across a variety of clinical and real-world settings.**

***Index Terms*—Laser Speckle Imaging, Biomedical Imaging, Optical Biosensing, Contactless Monitoring**

I. Introduction

The human skin surface encodes a lot of physiological information that goes far beyond what is captured by traditional monitoring of vital signs. Subtle changes in biomarkers such as perfusion, hydration, and topographical characteristics such as piloerection can reflect changes in autonomic nervous system activity and overall health. By tracking these subtle variations, it is possible to gain early insight into physiological stress, disease states, or responses to interventions. However, these aspects of skin function are largely invisible to mainstream wearable devices, which tend to focus primarily on heart rate and respiration [1]. Laser Speckle Imaging (LSI) offers a unique, non-contact means of visualizing and quantifying these structural skin changes along with the hemodynamic changes. By analyzing the dynamic patterns of scattered laser light, LSI can not only simultaneously assess blood flow, tissue hydration [2], and even fine surface features, such as the appearance of piloerection, also known as goosebumps, but also give other vital signs such as breath rate and heart rate. This multibiomarker capability positions LSI as a powerful tool for comprehensive physiological monitoring in a single optical measurement. Despite this versatility, devices such as PeriCam PSI or Moor Instruments are usually restricted to specialized laboratory or clinical settings, mainly due to the bulk, cost, and complexity of these systems [3]. As a result, the broader benefits of real-time, multiparameter assessment of skin remain untapped for wearable and, more importantly, point of care use.

This gap in accessible technology has tangible clinical consequences. For example, the timely detection of opioid withdrawal is a continuous challenge. Opioids account for 70% of the 0.5 million drug-related deaths each year, and this number continues to rise in part due to the lack of effective intervention and timely detection of opioid withdrawal [4]. Accurate detection of withdrawal is complicated by the variability of symptoms between individuals. Although physiological indicators like increased heart rate and rapid breathing are commonly seen during withdrawal, they are not reliable on their own. Both respiration and heart rate can be elevated for many reasons, including anxiety, pain, and other unrelated health conditions [5]. However, piloerection is highlighted as a key marker in the Clinical Opiate Withdrawal Scale (COWS) [6], and is considered more specific to opioid withdrawal than changes in heart or respiratory rate [7] [8]. This leaves a gap in accessible tools that extract standard vital signs with topographic skin features in real time, making it difficult for clinicians to reliably differentiate between opioid withdrawal and other conditions with overlapping symptoms.

To address this gap, we introduce SkinSpex: a compact, portable device that uses laser speckle imaging and speckle vibrometry through a multi-wavelength laser system, allowing measurement of perfusion as well as high-resolution detection of skin structure changes. Alongside these skin features, the device also tracks breathing and heart rate, providing a comprehensive physiological assessment. This cost-effective and noninvasive platform provides a comprehensive physiological profile and can support applications wherever acute, multi-system changes are relevant. Ultimately, SkinSpex lays the groundwork for next-generation wearable systems capable of real-time, continuous health monitoring by integrating multiple physiological and structural biomarkers.

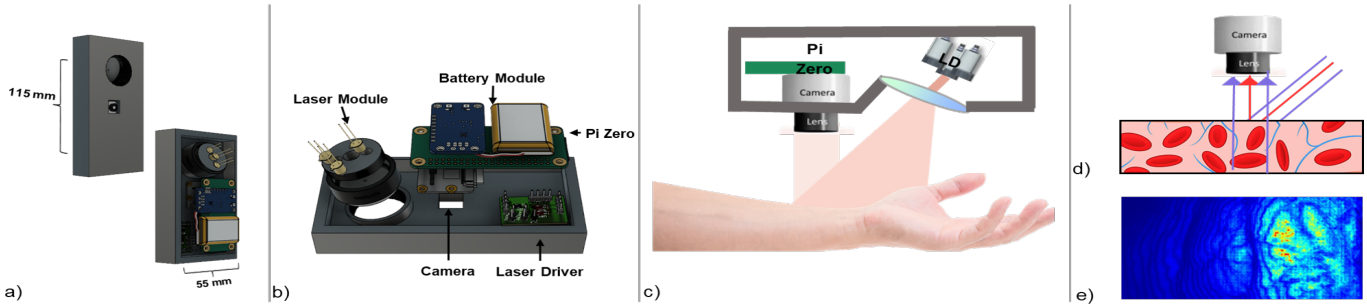

Fig. 1. (a) Side view of the device with the back cover removed, showing internal components. (b) Exploded view illustrating the arrangement of the Raspberry Pi Zero, battery, laser module, and control electronics inside the enclosure. (c) Schematic diagram of the working principle: the laser and camera modules are aligned for measurement on the skin using a diffuser. (d) Illustration of the laser speckle imaging process, showing how laser light penetrates tissue and is scattered by red blood cells. (e) Example perfusion map obtained from the system, demonstrating the final imaging result.

II. Materials and Methods

A. System Design

The SkinSpex prototype is designed to be portable and adaptable, prioritizing ease of use without compromising performance (Figure 1). Lightweight and unobtrusive, the system is easy to set up and features a Raspberry Pi Zero 2 at its core, eliminating the need for complicated installation. One side of the device holds a dedicated module for the lasers, each one securely mounted on the diffuser, with each beam aligned through its center. For uniform light distribution across the skin, we use a DG10-1500-MD 1500 grit diffuser from Thorlabs, which spreads the coherent laser light over a wider area and is firmly mounted within the enclosure. To capture data for perfusion, breath rate, and other parameters, we use three different laser modules, each chosen for its advantages. The setup includes a 520 nm green laser operating at less than 1 mW, a 750 nm near-infrared LED with a narrow 11-degree viewing angle producing approximately 18 mW at 50 mA, and a 930 nm infrared LED providing 15 mW at 50 mA.

We use a Raspberry Pi NoIR camera module for imaging, positioned directly in the optical path. This camera lacks an IR filter and can capture the full range of wavelengths from all three laser sources. It offers up to 8-megapixel resolution and supports adjustable frame rates (from 1 to 120 frames per second), variable focus, and a variety of shutter speeds. The entire system is powered by a compact, rechargeable lithium-ion battery. A dedicated battery driver manages stable power delivery to both the lasers and the Raspberry Pi, ensuring reliable operation. Laser activation and intensity are controlled by an onboard laser driver, with switching handled through the Pi. All device functionalities are managed via Python on the Pi Zero 2, and users can connect remotely over SSH to control the system, start and switch lasers, save and extract images, and adjust settings directly from a laptop. Altogether, SkinSpex offers a straightforward, portable solution for comprehensive skin imaging and perfusion monitoring.

B. Methods

Our prototype combines laser speckle contrast imaging and speckle vibrometry to extract a wide range of physiological and hemodynamic biomarkers. The choice of modality and configuration is determined by the feature being measured. For all measurements, the camera is set to a resolution of 640×480 pixels and the device is positioned 10 cm above the surface to be measured. This allows for manual focus adjustment, letting us switch between focused and unfocused imaging modes as required by each method.

1) Laser Speckle Contrast Imaging: Laser speckle contrast imaging is a non-contact imaging method for visualizing microvascular blood flow and tissue perfusion. When coherent laser light shines on a rough biological surface, the scattered photons create a very small interference pattern known as a speckle pattern. As red blood cells move through the illuminated area, the speckle pattern changes over time. By analyzing these changes, we can infer changes in blood flow, which helps calculate perfusion [8]. To quantify these changes, we calculate the speckle contrast (K), which is defined as the ratio of the standard deviation (σ) to the mean intensity ($\langle I \rangle$) within a sliding window:

$$K = \frac{\sigma}{\langle I \rangle} \tag{1}$$

In our implementation, a 7×7 pixel window is centered on each pixel and moved across the entire image, producing a local contrast map. This window size provides a practical balance: Smaller windows yield higher spatial detail but can amplify noise, while larger windows reduce noise but may blur critical features. The accuracy of speckle contrast measurements can be affected by several sources of noise, and environmental factors [9]. In particular, its use on the heartbeat calculations has been limited by motion artifacts [10]. To address these issues, we adjust acquisition parameters as detailed in section III.

2) Speckle Vibrometry: Speckle vibrometry is another non-contact method that measures subtle surface vibrations by analyzing the motion of laser speckle patterns reflected from the skin or other biological surfaces [11]. In this approach, the camera is deliberately unfocused to enhance sensitivity to small movements within the dynamic speckle field produced by coherent light scattering. By tracking the temporal changes

in the speckle pattern across regions of interest, it is possible to extract motion waveforms that reflect underlying physiological activity. Heart rate and respiration rate can be estimated from these waveforms using signal processing techniques, allowing for noninvasive monitoring of vital signs. This method is most effective when the measurement site is located near the heart, where the pulsatile signal is strongest. At the wrist, the signals are weaker and more prone to artifacts, making robust detection more challenging in practice.

III. Experimentation and Results

A. Perfusion

We evaluated skin perfusion using laser speckle contrast imaging with a 930 nm laser to obtain the raw speckle images. This wavelength was chosen for its ability to penetrate deeper into tissue, making it more sensitive to subdermal blood flow than visible light. To enhance the accuracy and reliability of our measurements, we recorded speckle images at 40 fps, employing two exposure times of 5 ms and 10 ms. The resulting perfusion maps were then averaged, resulting in a new map. This dual exposure method minimizes noise and increases the dynamic range. For a reference comparison of surface perfusion, we also captured FLIR thermal images. As shown in Figure 2, the general patterns observed in thermal imaging correspond well to those seen in our speckle-derived perfusion maps. The general agreement at the macroscopic level supports the validity of our method.

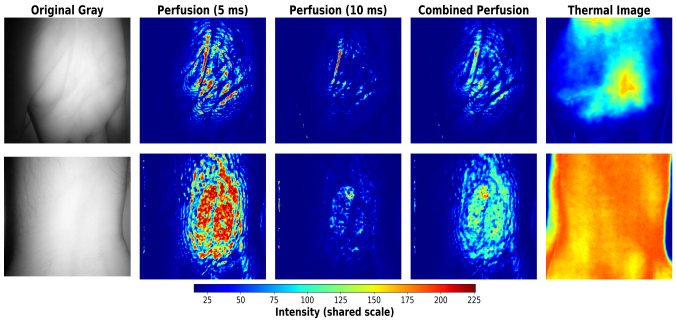

Fig. 2. Perfusion and thermal images for the palm (top row) and distal forearm region (bottom row).

To further validate our approach, we performed vein mapping on nearly the same anatomical region shown in Figure 2, the distal forearm or wrist, where visible veins are present. Vein structures were extracted using the Meijering filter applied to the speckle image obtained during the process of perfusion. Although this filter introduces some noise, it effectively highlights continuous, vein-like features. We then overlaid the resulting vein maps on the corresponding perfusion images. As shown in Figure 3, regions identified as veins consistently appear darker in the perfusion maps, indicating lower perfusion as expected. This spatial correspondence supports the reliability of our imaging pipeline. It is worth noting that such detailed vascular features are not visible in thermal images. Overall, our approach enables noninvasive mapping of both skin perfusion and vascular structure, with validation provided through cross-modality comparison.

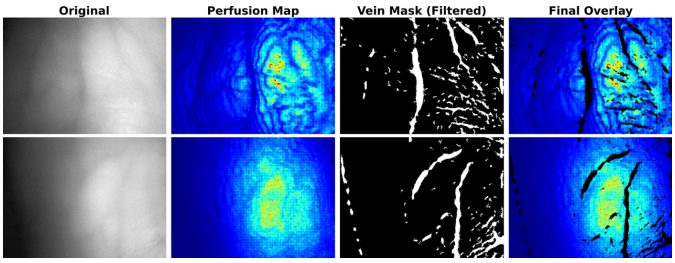

Fig. 3. Pipeline for vein localization: skin region, perfusion map, and predicted vein structures using the Meijering filter.

B. Skin Structure

For structural imaging, we used a 750 nm near-infrared laser and captured image sequences with longer exposures at low frame rates. This setup helps reduce motion blur and produces sharp images of the skin surface; the extended exposure time emphasizes static surface details while smoothing out transient speckle noise. We carefully adjusted the camera focus to reveal small features like pores and fine hairs. The analysis began with calculating local speckle contrast within temporal windows, which brought out persistent surface characteristics while minimizing the effects of rapid fluctuations. We then applied two complementary strategies: small, granular features (bumps and pores) were detected by identifying areas with abrupt intensity changes in the contrast map, while structures resembling hair were extracted using the Meijering ridge enhancement filter [12]. By combining the outputs of both approaches, we generated a composite map of the skin's microstructure, as shown in Figure 4.

To validate our approach, we used P40, P120, and P240 abrasive sandpapers as controlled standards for surface roughness. Our analysis demonstrated that P40, with its coarser grit, produced fewer but larger detected grains, while P240 yielded a higher count of smaller grains. Whereas P120 was in the middle of both, as summarized in Table I.

TABLE I
Size Analysis of Detected Surface Features for Sandpaper Grit: American National Standards Institute (ANSI) B74.12-2018

Sandpaper (ANSI)	**Grains** (count)	**Total Area** (mm^2)	**ANSI size** (μm)	**Measured Size** Mean (μm)
P40	917	609.1	425	664.1
P120	1089	358.2	125	328.8
P240	1710	275.5	50	161.1

The results show that our imaging and analysis pipeline can reliably distinguish differences in granular structure. Since these spatial scales overlap with physiological features such as goosebumps, the method can be directly applied to noninvasive monitoring of subtle structural changes in skin.

C. Breath Rate

To evaluate the performance of speckle vibrometry for respiratory monitoring, we captured speckle sequences using a 520 nm red laser in an unfocused configuration at 60 fps with a 15 ms exposure. The system was aimed at both the chest

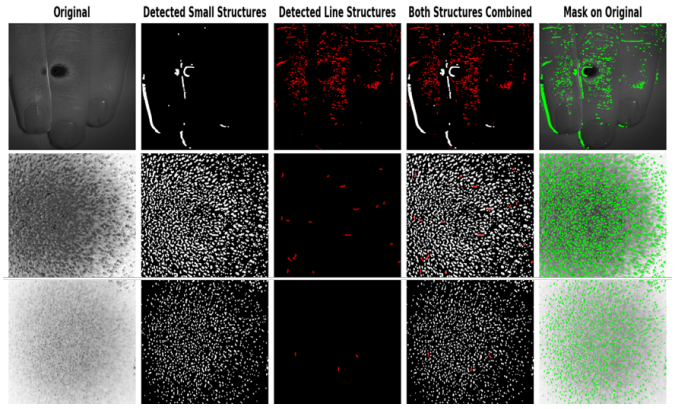

Fig. 4. Composite feature maps generated by the analysis pipeline: (Top) example from human skin, (Center) P40 sandpaper, and (Bottom) P240 sandpaper. Detected granular and linear features are overlaid for each sample.

and the wrist to compare signal quality across anatomical sites. As shown in Figure 5, the respiration signals extracted from both locations are plotted alongside the reference waveform recorded using the Bitalino system from PLUX Biosignals. In each reading, the region of interest was divided into a grid of sub-ROIs, and subpixel shifts between consecutive frames were computed using phase-based registration. The resulting motion traces were then combined using principal component analysis to extract a clean respiration waveform. The chest region was selected as a baseline due to its stronger respiratory motion and direct coupling with lung expansion. The extracted waveform from the chest exhibits a clear periodic structure and closely tracks the reference signal, though some minor discrepancies remain. In contrast, the wrist signal is weaker, more irregular, and more susceptible to motion artifacts, reflecting the reduced mechanical displacement in distal regions.

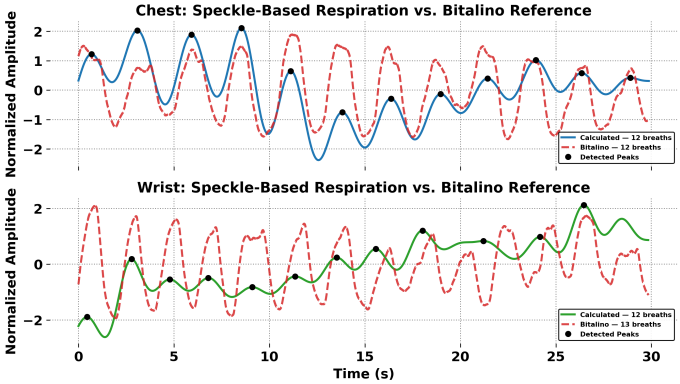

Fig. 5. Comparison of speckle vibrometry-based and reference respiration signals from chest and wrist locations.

IV. Conclusion

In this paper, we introduced SkinSpex, a compact and portable prototype designed for noninvasive monitoring of both hemodynamic and structural skin features. Leveraging LSI, an underutilized yet powerful optical technique, SkinSpex simultaneously captures skin perfusion, vascular patterns, respiratory motion, and surface morphology, providing comprehensive insights into physiological states. Our results demonstrate that SkinSpex is capable of reliably measuring these physiological parameters and highlight its potential as an integrated, multimodal platform for advanced monitoring. Looking ahead, our goal is to transition SkinSpex into a wearable form factor, enhancing its functionality for continuous, real-time monitoring intuitively and unobtrusively. We plan to refine respiratory signal extraction techniques and incorporate additional biomarkers such as hydration and heart rate, further broadening its applications in clinical and wellness settings. We believe LSI-based systems like SkinSpex can serve as comprehensive, single-point solutions for capturing vital signs and additional physiological data.

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