Imaging Photoplethysmography to Determine Pressure Induced Changes in Cutaneous Blood Volume

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***Abstract*—The assessment of cutaneous blood volume in the hand and its response to external stimuli is crucial for many innovative techniques in medicine, including guiding research in optical peripheral implants. However, traditional methods for measuring blood flow dynamics, such as Laser Doppler Flowmetry (LDF) and Hyperspectral Imaging (HSI), demonstrate limitations in field-of-view of analyzed tissues. The emergence of imaging photoplethysmography (iPPG) has enabled both non-contact and spatially resolved measurements of cutaneous perfusion. In this study, we present the implementation of iPPG to investigate pressure-induced changes in cutaneous blood volume within the hand. We have successfully developed an iPPG system capable of capturing perfusion changes in the hand under varying pressure conditions. High-resolution imaging, along with advanced image processing algorithms, were employed to extract physiological information from specific videos of the hand under different forces. A microscope stand mounted with a camera, ultrawide-angle lens, LED ring, and 3D printed clear-resin force probe were used to obtain high-resolution videos of the volar hand surface. The Plane-Orthogonal-to-Skin algorithm was then utilized to provide spatial maps of cutaneous perfusion in the hand. This project not only advances our understanding of cutaneous vascular dynamics in the hand but will guide the design of peripheral brain-computer interface implants. Furthermore, it will contribute to the development of optical PPG peripheral force sensors by identifying ideal implantation locations in the hand.**

***Index Terms*—force, imaging photoplethysmography (iPPG), machine learning, optical sensors, perfusion, photoplethysmography (PPG), python**

I. Introduction

Tactile feedback plays a vital role in movement control, especially in the intricate movements of the hands at the level of the intrinsic hand muscles, where skin mechanoreceptors are highly concentrated. Restoring functional movements in paralysis patients through brain-body connections (neuroprostheses) would be incomplete without tactile feedback. This can be achieved by stimulating somatosensory brain areas in response to tactile signals acquired by sensors on the desired effector [1].

Previously, our lab developed an implantable artificial mechanoreceptor (IAM) capable of acquiring tactile signals [2]. The IAM, a wireless hermetically sealed device, sensed forces acting on the skin capacitively from beneath the skin surface [3]. However, its sensitivity is limited in detecting forces above the subcutaneous space, which is well below the normal anatomical location of mechanoreceptors.

As an alternative approach, it is easily observable that forces transiently affect skin color due to blood volume changes in the compressed skin capillaries. Optical measurements on the fingernail have previously used this effect to sense forces applied to the fingertip [4]. Building on this observation, we hypothesize that a miniature subcutaneous device could optically assess the blood volume in the overlying dermis, creating a sensitive tactile sensor for neuroprosthetic applications (Fig. 1).

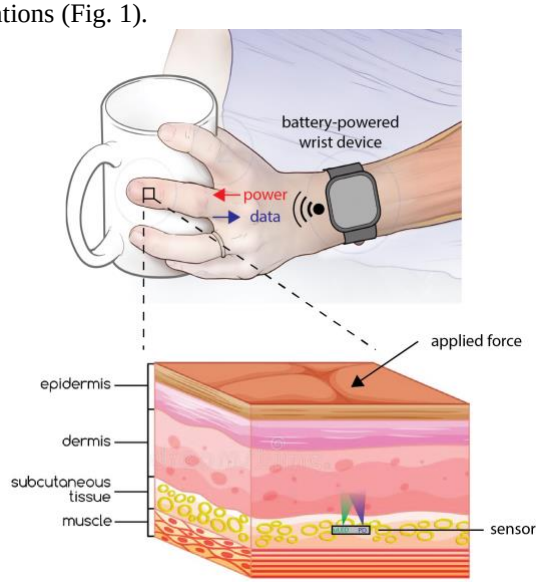


Fig. 1 *Proposed Sensor Application*

To design this sensor rationally, it is essential to understand the spatiotemporal properties of blood volume changes in response to tactile forces. Among the non-invasive techniques available, imaging photoplethysmography (iPPG) has emerged as a promising method to study these cutaneous perfusion dynamics.

Photoplethysmography (PPG) is a well-established technique that measures variations in blood volume using optical sensors [5]. Traditional PPG employs contact sensors placed on the skin surface, typically at the fingertip or earlobe, to monitor blood flow dynamics. However, these conventional PPG methods are limited in their ability to provide spatial information regarding cutaneous perfusion and its response to localized stimuli.

The advent of imaging photoplethysmography (iPPG) has enabled non-contact and spatially resolved measurements of cutaneous perfusion [6]. iPPG utilizes video-based imaging systems to capture subtle variations in skin coloration resulting from the blood volume changes in superficial blood vessels. By analyzing the temporal color intensity variations, iPPG can estimate blood flow dynamics.

Most existing applications of iPPG are targeted towards bleed detection during surgeries [6], but none have been designed for the observation of microcirculation. In this project, we present the implementation of iPPG as a novel approach to investigate pressure-induced changes in cutaneous perfusion. The application of pressure on the skin surface can modulate blood flow, leading to alterations in microvascular dynamics [7]. By utilizing iPPG, we aim to elucidate the spatiotemporal patterns of cutaneous perfusion under varying pressure conditions.

The primary objective of this study is to develop an iPPG system capable of capturing perfusion changes in the hand in response to pressure stimuli. We will employ a high-resolution imaging system to acquire video sequences of the volar hand region of interest. Subsequently, advanced image processing algorithms will be employed to extract relevant physiological information from the acquired data.

The successful implementation of this project on iPPG and pressure-induced changes in cutaneous perfusion will enable future research into both biomedical diagnostics and guide peripheral brain-computer interface implant design. In particular, this project improves our understanding of ideal implantation locations in the hand for optical PPG peripheral force sensors [8], [9].

II. Background

A. Traditional Methods for Measuring Perfusion Dynamics

Traditional examination of microvascular motion dynamics has employed techniques like laser doppler imaging (LDI) and laser doppler flowmetry (LDF), which rely on detecting reflected or transmitted light and analyzing doppler-shifted signals [10], [11]. A newer method, hyperspectral imaging (HSI), shares the capability of detecting tissue oxygen distribution. However, it acquires a 3D dataset called a hypercube, comprising spectral bands at each pixel within a 2D image. This dataset empowers HSI to achieve high spatial and spectral resolution images [12]. Nonetheless, these techniques suffer from severe limitations concerning their maximum field-of-view (FOV).

B. Blood Flow Dynamics

Prior investigations into skin microcirculation have unveiled the existence of various adaptive vasodilatory mechanisms that play crucial roles in maintaining adequate blood supply and control within the body [13], [14]. A few worth noting are myogenic control, endothelial metabolic activity, and pressure induced vasodilation (PIV). These mechanisms involve intricate processes within blood vessels, capillaries, and surrounding tissues, dynamically responding to changes in physiological conditions. Knowledge of the existence of these blood flow dynamics is essential to help explain observable phenomena generated by our system and experiments.

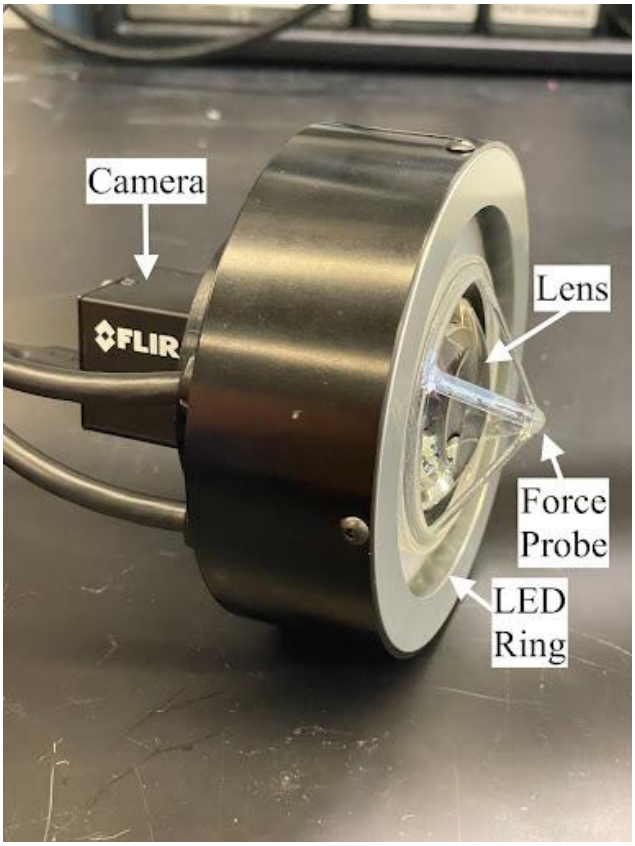
III. Materials and Methods

A. Experimental Equipment, Setup, and Process

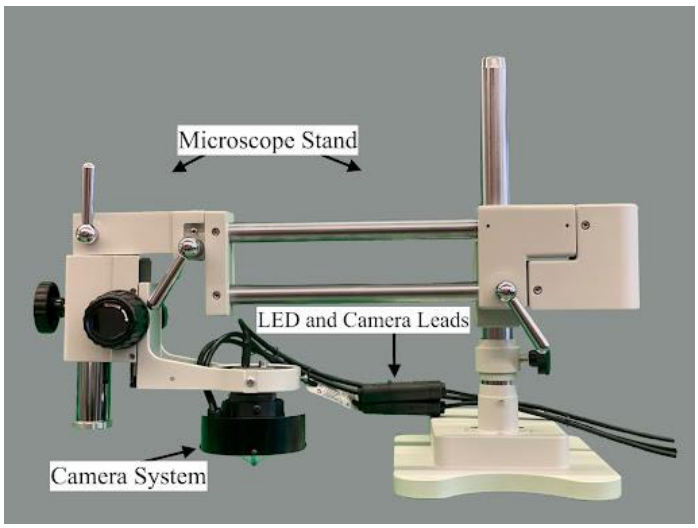
Our iPPG system contains a 3.2 Megapixel RGB camera (Blackfly BFS-U3-32S4C-C, Teledyne FLIR, Wilsonville, OR) with a resolution of 2048x1536, paired with a 3.5mm Lens (Max Aperture F2, Edmund Optics, Barrington, NJ), and an LED ring (RL5604 WHITE, Advanced Illumination, Rochester, VT). The camera can receive a spectral band within the visible light range (400-700 nm). The lens is designed for a working distance (WD) of 0- ∞ mm with a horizontal FOV of 102.4° and a vertical FOV of 82.3°. A force probe was then 3D printed using a Form 3B+ printer from Formlabs (Boston, MA) using clear resin and attached to the end of the lens for the force testing. The force probe had a hemispherical tip (5mm diameter), measuring 16 mm from the tip to the convexity of the lens.

Figure 2a provides a close-up view of the camera system along with its attachments. To ensure stable control of the imaging setup, we mounted the system on a larger microscope stand, as depicted in Figure 2b. For video recording, we utilized the GUI application SpinView (Spinnaker SDK, Teledyne FLIR, Wilsonville, OR) on our laptops via a USB3 interface, capturing 20-second videos at 60 frames per second. Subsequently, to optimize memory usage and algorithm run time, we compressed these video files to a resolution of 1920x1080. With a total frame area of 62cm^2, our system is capable of a spatial resolution of 0.547 mm/pixel.

In the video processing phase, we primarily used Python 3.11. By analyzing the RGB values of each pixel throughout all video frames, we extracted blood flow information. Our program utilized spatial and temporal normalization techniques, along with the Plane-Orthogonal-to-Skin (POS) algorithm and an additional frequency filter, to derive blood volume information from each pixel. The POS algorithm uses a projection matrix orthogonal to the plane of skin to remove the influence of skin tone from intensity measurements. It also makes use of the fact that blood hemoglobin preferentially absorbs green and red light compared to blue. [14]. For an extensive explanation of the POS algorithm, refer to the publication by Wang et al. After processing, output videos were produced at the same frames per second and resolution.



(a)



(b)

Fig. 2 *(a) Close-up Image of Camera System (b) Entire iPPG Experimental Setup*

B. Calibration Testing

Before proceeding with the force probe study to investigate the effects on cutaneous vasculature in the hand, we conducted a preliminary test to assess our program's capability to detect blood volume changes in the body. For this purpose, we simultaneously recorded a video 1 inch away from the forearm area near the wrist and obtained a PPG signal using a pulse oximetry sensor placed on the index finger (Fig. 3). Subsequently, we processed the video in 5 second intervals through our program, applying a frequency filter with a bandwidth of 0.67-4.00Hz, which covers the physiologic human heart rate range (40BPM-240BPM). The output of this program gave us a video depicting the changes of the normalized blood volume within the arm to hand area over 5 second intervals. Our primary objective was to synchronize the output video, depicting blood flow pulses, with the pulse signal received from the sensor. Accounting for the difference in location of the video and the sensor, we decided to only attempt correlating the time in between each heartbeat in the PPG signal and blood pulse in the video. We would deem our system successful and ready for force testing once our program produced pulses in phase with the true pulse signal.

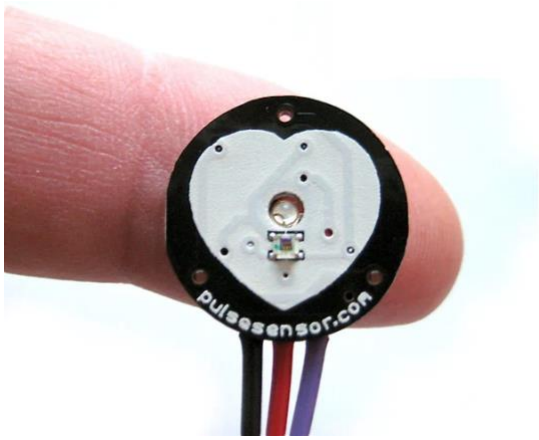


Fig. 3 *Pulse Oximetry Sensor Used (PulseSensor, World Famous Electronics llc., NY) Adapted from: Pulsesensor.com*

C. Force Induced Changes in Cutaneous Perfusion

After confirming the capability of our iPPG system to image blood volume changes beneath the skin, we decided to modify our experiment to observe force-induced changes in cutaneous perfusion. To achieve this, we attached the force probe to the camera and recorded a 20-second video of the hand from approximately 1 inch away (Fig. 4). The video captured the sequence of events starting with direct contact between the hand and the probe. The probe was then moved from the center of the palm medially, reaching the level of the 5th digit, and finally translated distally to the MCP joint.

To analyze the effects of force-induced changes in cutaneous perfusion, we adjusted the frequency filter in our program to have a bandwidth of 0.0095-0.145Hz. This specific range encompassed the physiological bands of the adaptive vasodilatory mechanisms we expected to observe within the hand's microcirculation. These mechanisms include myogenic, neurogenic, and endothelial activity [13]. Upon completing this process, the outcome is a normalized cutaneous blood volume (CBV), which serves as an indicator of blood presence in the microcirculation of a specific area. We generated a video over the middle 18 seconds of the video, demonstrating the fluctuations and changes in CBV over time. These videos show the dynamic alterations in cutaneous blood volume throughout the observation period.

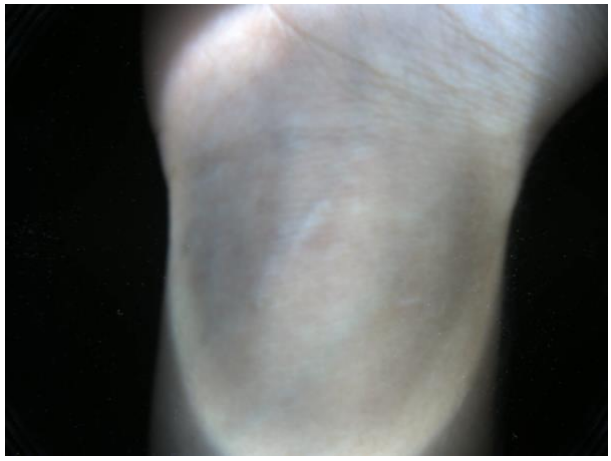
Fig. 4 *iPPG Experimental Setup to Capture Force Induced Changes in Cutaneous Blood Volume*

IV. Experimental Results

In this section, we present the results of our investigations using the iPPG system to assess blood volume changes and visualize force-induced alterations in cutaneous perfusion within the hand. Initially, we confirmed the system's efficacy in capturing blood volume changes over a higher frequency bandwidth by developing correlations between the iPPG output and PPG signal obtained from a pulse oximetry sensor. These correlations laid the groundwork for our subsequent research objectives. Leveraging this capability, we then tailored our approach to focus specifically on imaging force-induced vascular responses. Through our refined iPPG implementation, we successfully acquired comprehensive cutaneous blood volume (CBV) information, covering a large area of the hand. The analysis allowed us to visualize changes in CBV, providing valuable insights into the microcirculatory autoregulatory mechanisms at the point of contact and surrounding tissues.

A. Calibration Testing

In our conducted test, we successfully obtained images of blood flow in the arm and hand region, revealing variations in the normalized blood volume. As illustrated in Figure 5a, a single frame from the original forearm video captured during the experiment is presented. Additionally, Figure 5b and Figure 5c display two distinct mapped iPPG outputs taken approximately 0.33 seconds apart. The iPPG map is represented on a signal intensity scale, showcasing the normalized iPPG blood volume signal, ranging from 0 to 1. The red areas indicating a higher concentration of blood, whereas the blue areas indicated the opposite.



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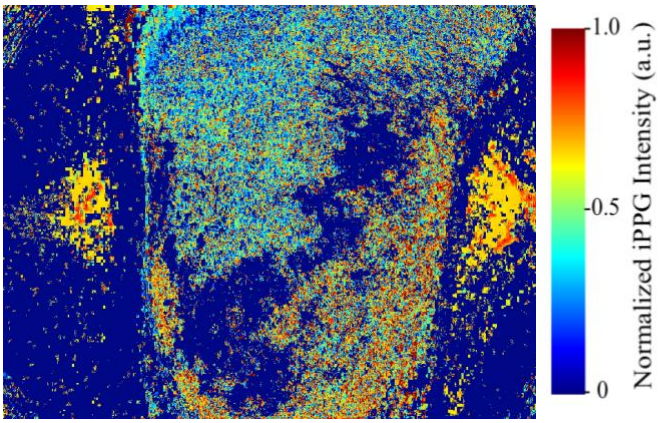

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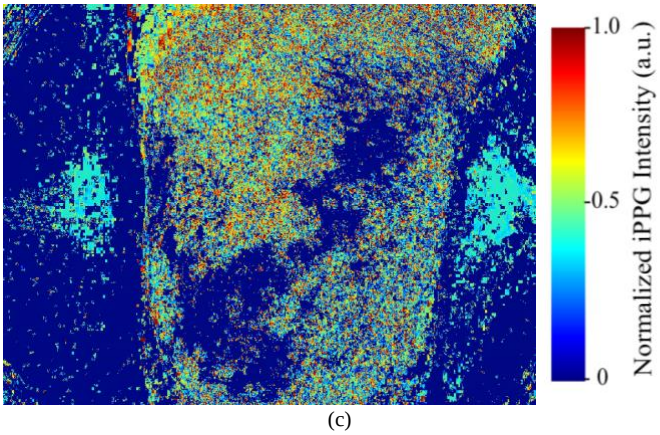


(c)

Fig. 5 *(a) Frame from the original video of forearm and wrist region at a 1-inch distance. (b) Mapped iPPG output at same time point as original image in (a). (c) Mapped iPPG output around 0.33 seconds after the images in (a) and (b).*

Next, we proceeded to successfully correlate the cyclic blood movements observed in the output video with the PPG signal generated by the pulse oximetry sensor (Fig. 6). Given the placement of the sensor on the finger and the imaging focused on the forearm, our analysis focused on matching the

time intervals between each heartbeat in the PPG signal and the blood pulses observed in the mapped iPPG video.

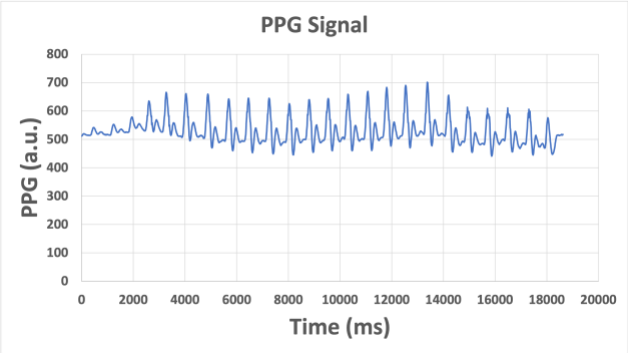
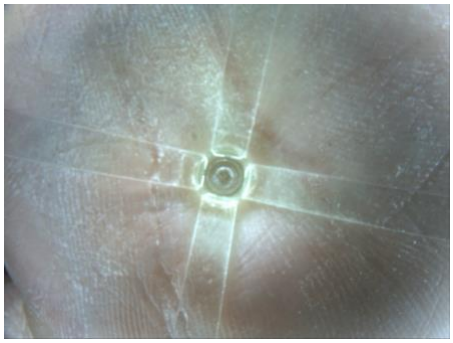


Fig. 6 *PPG Signal Produced from the PulseSensor During Experiment*

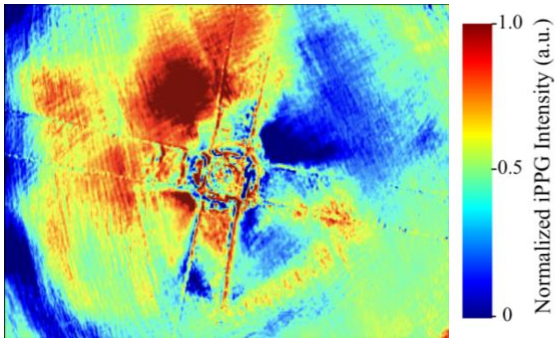
B. Force Induced Changes in Cutaneous Blood Volume

Having successfully confirmed our system's capability to image blood volume changes on a larger frequency scale, we advanced to our specific implementation of iPPG aimed at visualizing force-induced changes in cutaneous blood volume within the hand. To do so we lowered our frequency range of interest to a bandwidth of 0.0095-0.145Hz, capturing the bands of the adaptive vasodilatory mechanisms expected in the hand. Through this tailored approach, we were able to obtain comprehensive CBV information, effectively encompassing a substantial portion of the hand, and capturing changes within an area of approximately 62 cm^2. The capability of viewing a large area is particularly crucial, as our iPPG device aims to observe microcirculatory autoregulation effects precisely at the point of contact and in the surrounding tissue, thereby facilitating optimal sensor implantation guidance.

Figure 7a exhibits one frame of the original hand video captured during the experiment, while Figure 7b displays the corresponding mapped iPPG output at the same time instance. At this time instant the probe was moving downwards and to the left in relation to the image. The iPPG map is again represented on a signal intensity scale, showcasing the normalized iPPG blood volume signal, ranging from 0 to 1. The red areas indicating a higher concentration of blood, whereas the blue areas show the opposite. Moreover, Figure 8 demonstrates the power spectrum obtained for the specific frequency range of interest, providing additional validation for our analysis of this frequency region. Notably, all frequency values within our designated bandwidth exhibit a relative consistency, bolstering the reliability of our findings within our bandwidth of interest.



(a)



(b)

Fig. 7 *(a) Frame from original video showcasing the probe in direct contact with the hand. At this point the probe was moving downwards and to the left in relation to the image. (b) Image produced demonstrating the mapped CBV on a normalized iPPG signal intensity scale (0-1).*

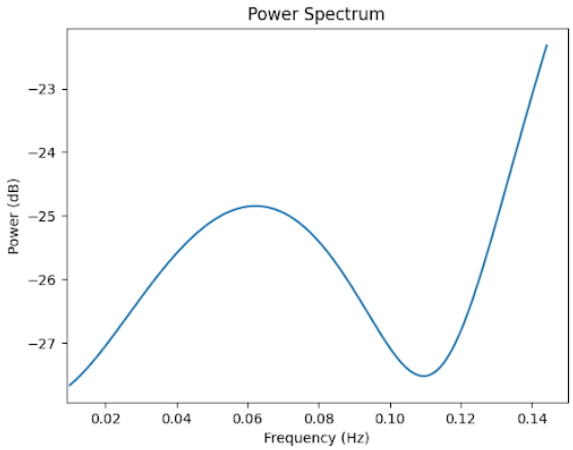
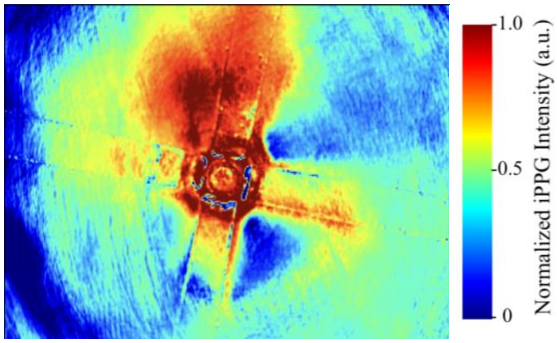


Fig. 8 *Power Spectrum Produced Over the Targeted Frequency Range*

Our test also had brief moments where the probe became static on the hand and had stopped moving. The resulting blood flow response after around 1 second stopped is shown in Figure 9 below.



Fig, 9 *Image produced of the mapped CBV on a normalized iPPG signal intensity scale (0-1) after the probe had stopped moving for around 1 second.*

V. Discussion and Conclusion

In our preliminary model testing, we achieved a successful correlation between the cyclic blood movements observed in the output video of the arm and the PPG signal generated by the pulse oximetry sensor. This cyclic blood flow can be distinctly observed during the transition from Figure 5b to Figure 5c, where the blood pulsates towards the hand, away from the forearm region. This consistent trend persisted throughout the 5-second clip, aligning precisely with the corresponding PPG signal. The strong concurrence between the observed blood volume trends in the video and the PPG signal enabled us to confidently affirm the sensitivity and accuracy of our system in detecting and capturing blood flow dynamics within the body.

Upon modifying our program to analyze microcirculation and progressing with force application experiments on the hand, we made several intriguing observations regarding blood flow dynamics. Figure 7b offers valuable insights into the impact of normal forces, even at low levels (<10mmHg), sustained for brief durations of 1-2 seconds. This force application led to the displacement of blood away from the point of compression (POC), as evident in the "blue void" trailing the POC. This phenomenon indicates reduced CBV due to adaptive vasodilatory mechanisms lagging the moving compression wave. This lagging is anticipated due to the comparatively slower myogenic control and endothelial metabolic activity in response to the probe's movement, which is advancing at approximately ~1cm/sec along the palm. However, this initial response was followed by a notable increase in perfusion in the affected area, as these adaptive mechanisms eventually caught up and effectively resupplied the surrounding tissue (Fig. 9).

Furthermore, Figure 9 showcases the reaction when the force application remained stagnant on the hand. The image reveals a rapid increase in perfusion occurring at 1-second intervals from the surrounding tissue microcirculation. This consistent pattern demonstrated a well-known phenomenon called pressure-induced vasodilation. PIV arises due to myogenic activity at compressed precapillary sphincters and resistance vessels [14]. Interestingly, the surrounding microcirculation appeared to prioritize supplying the tissue experiencing sustained normal forces as part of PIV, rather than the surrounding tissue that had been previously subjected to force application (Fig. 7b and Fig. 9).

Previous research demonstrated the utility of iPPG in detecting AC signals within the physiological heart rate bandwidth (0.67-4Hz). Building upon these findings, our study goes further to reveal that iPPG has the capability to accurately resolve high-resolution images of microcirculation even at near-DC (direct coupling) bandwidths, without introducing considerable noise. This capability has allowed us to demonstrate the visualization of pressure-induced changes in microcirculation perfusion, with documented autoregulation methods contributing to the observed phenomena. This extends the applicability of iPPG as a versatile and effective tool for visualizing microcirculatory dynamics with enhanced precision.

Moving forward, we have devised a new testing apparatus in our lab, integrating an XYZ-force stage to apply precise forces to the hand. This enhanced precision enables us to control the magnitude and types of force applied, facilitating a comprehensive exploration of microcirculatory blood flow dynamics and its response to various forces within the hand. By gaining deeper insights into these dynamics, we can proceed to implement our novel implantable optical sensors. Armed with this newfound knowledge of how pressure affects blood flow, we aim to accurately indicate the location and magnitude of applied force, mimicking the sensation of touch. This innovative approach holds significant promise in aiding paralysis patients, paving the way for potential advancements in neuroprostheses and rebuilding their sense of touch.

Acknowledgment

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