Camera-based Plantar Perfusion Imaging for Detecting Lower Limb Arterial Blockage

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***Abstract*— Lower limb arterial blockage (LLAB) is an early symptom of peripheral arterial disease (PAD), a common circulatory problem caused by the accumulation of fat and cholesterol in arteries as a result of atherosclerosis in the lower limbs. PAD can be diagnosed by detecting LLAB, which blocks the blood flow from leg to foot and causes a decrease of plantar blood perfusion. Camera-based photoplethysmographic imaging, a non-contact imaging technique for measuring skin perfusion, is a potential tool to detect LLAB for the early diagnosis of PAD. Cameras have been used for vital signs monitoring, such as heart rate, respiration rate and blood oxygen saturation, but its potential for PAD analysis has not been explored. In this paper, we investigate the new concept of using a regular camera to measure the skin perfusion of plantar for LLAB detection. Instead of imaging the facial skin perfusion as current vital signs camera, we use the camera to analyze the blood perfusion of plantar skin surface. We constructed an imaging setup and designed a lab-simulated experiment involving 20 subjects, where an inflatable cuff is applied to block the blood flow of the left leg to simulate LLAB. The experimental results show that the camera-based plantar perfusion imagers can clearly differentiate between the leg applied with cuff (simulated LLAB) and the leg in the normal state.**

***Index Terms*—Lower limb arterial blockage, perfusion imaging, camera-based pulse wave, peripheral arterial disease.**

I. INTRODUCTION

Peripheral arterial disease (PAD), an atherosclerotic condition that affects tens of millions of people worldwide, frequently leads to limb pain, gangrene, amputation, and other serious consequences, threatening the human health [1]. Early diagnosis of PAD is important for determining appropriate treatment strategies, which can ultimately improve the patient's prognosis [1], [2].

Lower limb arterial blockage (LLAB) is an early manifestation of PAD and therefore its detection allows for the early diagnosis of PAD [3]. In clinical scenarios, LLAB is detected, located and assessed by medical instrumentations such as ultrasound doppler, computed tomography (CTA), and ankle brachial index (ABI) [1]. Although these methods provide metrics to quantify blood flow and vascular anatomy, they have inherent limitations for large-scale applications such as high-cost, complexity of the examination procedure, and inaccessibility at homes or community hospitals [4]. Effective, cost-efficient, and ubiquitous tools for PAD diagnosis are thus desired.

Photoplethysmography (PPG) is a non-invasive and low-cost optical sensing technology that captures pulse wave information by measuring blood volume changes in arterial vessels [5]. PPG already has a wide range of applications in patient care and assisted-living [6]. This has also sparked interest in using it to assess arterial vascular health. Xu et al. [7] investigated its performance in predicting atherosclerosis based on the measurement of brachial-ankle pulse wave velocity (baPWV) from multiple PPG sensors attached to brachial and ankle. They showed that when baPWV exceeds 2100 cm/s, vessels can be blocked due to atherosclerosis. Peltokangas et al. [8] used the pulse wave systolic rise time (SRT) of PPG measured from toes to assess the hemodynamic status of patients with PAD, where SRT shows high correlations with the severity of PAD (degree of arterial blockage). Moreover, abundant PPG features such as the pulse arrival time and pulse wave amplitude are extracted for diagnosing PAD [9]. However, the limitation of PPG is that it is a single-point sensing modality, which cannot be used to measure rich spatial information of plantar perfusion (e.g. pulsatile distribution) for potentially more accurate diagnosis.

Recently, a non-contact PAD diagnostic approach exploiting thermal imaging to detect changes in plantar temperature has been investigated [10]. The measurement principle is that arterial stenosis or even the obstruction of blood flow in lower limbs caused by PAD can lead to chronic or acute ischemia in the tissues of lower limbs (e.g. plantar surface), so as to the asymmetric temperature of two feet due to different blood supply conditions [3]. According to the blood circulation and human thermoregulation, LLAB affects blood perfusion first (i.e. perfusion refers to the blood pulsation in skin tissues) and then the skin temperature [11]. This means that LLAB changes the plantar PPG upfront the plantar temperature, i.e. the PPG contrast should be observed before the temperature contrast at plantar surface. In this sense, camera-based photoplethysmography (camera-PPG) that can image the skin perfusion remotely [12], [13] is a potential tool for LLAB detection. Although its accuracy in monitoring cardio-respiraitory parameters has been shown in various high-acute clinical settings [14], [15], its potential role for PAD diagnosis has not been investigated.

This paper focuses on investigating the feasibility of using camera-based plantar perfusion imaging to detect LLAB, which exploits the advantage of imaging property (i.e. pixel arrays) of the camera sensor to provide a pulsatile distribu-

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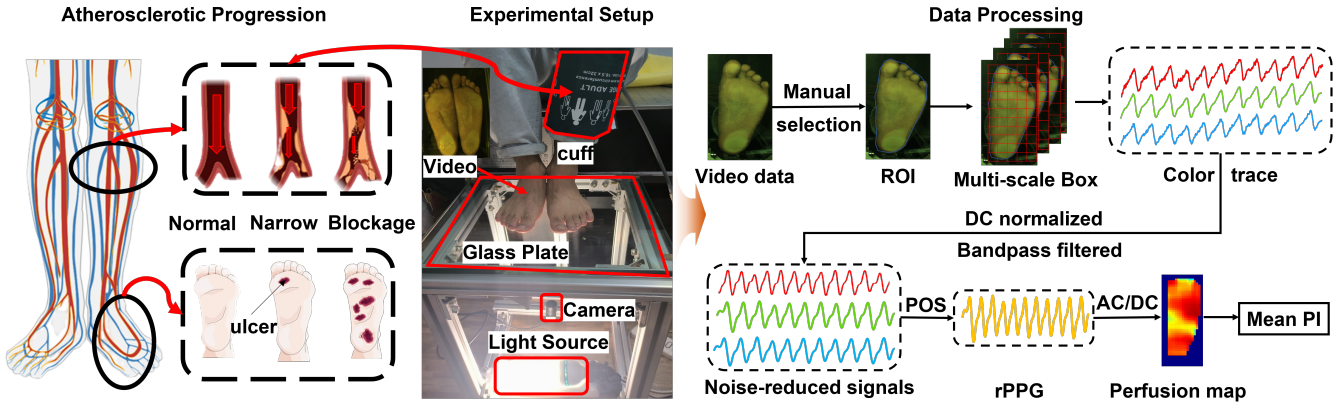


Fig. 1. The experimental setup and algorithmic framework for generating the plantar perfusion imagers.

tion map of the plantar surface. In order to investigate the impact of LLAB on plantar perfusion, we designed a lab-simulated experiment. An RGB camera is used to record the plantar video for PPG-signal extraction. An inflatable cuff was worn on the subject's left leg to simulate a blockage of the artery, while the right leg was kept in the normal state as the reference for comparison. A total of 20 subjects participated in this experiment. We exploit the spatial redundancy of the image sensor [16] to perform multi-scale segmentation of the plantar images to obtain clean PPG signals from subregions, and further calculate the perfusion index (PI) of the subregions to generate the perfusion map. We analysed the impact of LLAB on plantar perfusion in two ways: (i) analyzing the distribution and intensity of blood perfusion from the perfusion map; (ii) analyzing the mean PI (MPI) by averaging the plantar perfusion index. Preliminary results show that when the left leg is compressed by a cuff (i.e. lower limb arterial vessels are blocked), there is a clear drop in the PPG amplitude of the plantar skin of the left foot and thus a significant decrease of MPI. Such phenomenon was reproduced on 20 test subjects. Thus we consider camera-PPG based plantar perfusion imaging to be a viable method for LLAB detection.

II. METHODS

A. Experiment

A total of 20 healthy subjects (15 males, 5 females, aged 21.6 ± 3.6 years, height 172.3 ± 7.4 cm, weight 61.9 ± 9.6 kg) were recruited for this experiment. The study was approved by the Institutional Review Board of Southern University of Science and Technology, and written informed consent were obtained from the test subjects.

1) Experimental Setup: Fig. 1 shows the schematic diagram of the setup for the LLAB simulation, with detailed descriptions of the components as follows:

- Camera (IDS-UI3860C). It was used to record videos from the plantar surface of feet at 60 frames per second with 960×468 pixels. The videos were saved in the raw image format for lossless PPG-signal extraction.
- Light source (100 w incandescent lamp). An incandescent light source with a continuous spectrum of 400-1700 nm is used. To avoid the stroboscopic phenomenon generated by AC power supply, an AC to DC converter is used to provide a stable DC power supply.
- Glass plate. It allows the subjects to place their feet naturally on the glass surface to stabilize the feet for eliminating the foot motion.
- Inflatable cuff. It is used to exhibit pressures on the leg to block the blood flow in order to simulate the LLAB.

The glass plate is supported by aluminum tubes with the camera and light source placed 40 cm below it (see Fig. 1). The camera is connected to the computer via USB 3.0 and the recording is controlled by a software.

2) Experimental Protocol: During the experiment, the subject sat on a chair with its feet naturally positioned on the glass plate. The whole experiment consists of three stages:

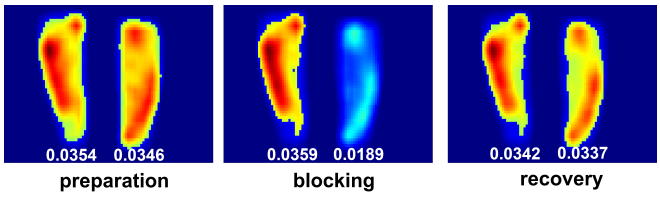
- Preparation stage (30 s). Subject remained stationary to record the perfusion of both feet in the non-obstructed state.
- Blocking stage (30 s). Pressure is applied to the subject's left leg by an inflatable cuff, the increased pressure occluded the blood flow from leg to foot.
- Recovery stage (60 s). The cuff stops inflating and the pressure is quickly released.

B. Plantar Perfusion Map Generation

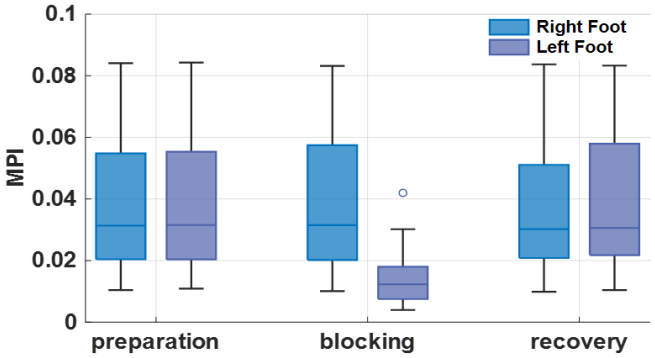
1) Multi-scale segmentation: First, the plantar area of the foot was manually selected as the region of interest (ROI), and the areas corresponding to the left and right foot are denoted as ROI_l and ROI_r, respectively. As the ROI is not a rectangular shape, the outer rectangles of ROI_l and ROI_r are divided into boxes using multi-scale segmentation (40×40, 50×50, 80×80, 100×100 pixels with 50% overlap). For boxes containing both ROI and non-ROI pixels, the inpolygon function of Matlab2021b is used to select valid pixel (within the ROI) for subsequent calculations.

2) PPG extraction: The pixel averages of the R, G and B channels of each box in ROI_l and ROI_r are extracted separately to generate the RGB traces. The RGB traces are then processed as follows:

- DC normalization. The DC component is normalized with zero-mean subtraction.
- Bandpass filtering. A 4-th order Butterworth filter with cut-off frequency of [0.5, 4.0] Hz is used to filter the DC-normalized RGB traces.



(a) Plantar perfusion maps of the left and right foot of a subject.



(b) Boxplots of the MPI for the plantar surface of 20 subjects

Fig. 2. (a) shows the blood perfusion of plantar surface of two feet across three stages. Brighter color indicates stronger pulsatility. The numbers denotes the MPI of the left and right foot respectively. (b) shows the statistical distribution of plantar MPI of 20 subjects.

- Channel fusion. The plane-orthogonal-to-skin (POS) algorithm [17] is used to fuse the filtered RGB traces into a PPG signal, where distortions are suppressed by channel combination.
- PPG imaging. The AC of spatial-redundant PPG signals are calculated to render a PPG imager [18] that shows pulsatile distributions on the plantar surface.

3) PI calculation: PI is derived from the PPG imaging signals, which reflects the ratio of pulsatile and non-pulsatile absorption of the light in the PPG signal. It can be calculated as AC/DC of the PPG signal [11]. As the DC normalization has been performed during the PPG extraction, only the AC component of the PPG signal needs to be calculated to obtain the PI, i.e. by taking the standard deviation of the PPG signal within a time interval such as using the duration of each experimental stage to calculate the PI for each stage.

The video data recorded by the camera were divided into three clips according to the duration of each experimental stage. For each video clip, the PI of each box in ROI_l and ROI_r was calculated to generate the perfusion maps. The MPI of ROI_l and ROI_r was also calculated separately.

III. RESULTS AND ANALYSIS

We assessed the impact of LLAB on plantar perfusion by analysing the perfusion map and MPI. The perfusion map shows the spatial distribution of pulsatile component, while the MPI indicates the averaged pulsatile strength of plantar.

Fig. 2 shows the perfusion changes in both feet over the three stages. In the preparation stage, the plantar perfusion of the left and right foot is rather similar, including both the perfusion maps and MPI values. In the blocking stage, the perfusion of the left foot was significantly decreased as compared to the right foot, giving lighter heatmap color and lower MPI values. In the recovery stage, perfusion in the left foot returned to a level close to that of the right foot, shown by both the perfusion maps and MPI values. Based on the above observations, we have following verdicts: (i) when the leg is in the normal state, the plantar perfusion of the right and left foot remains relatively consistent and similar; (ii) when the leg is compressed by the cuff, blood flow is blocked and it leads to a significant decrease in plantar perfusion. When the cuff pressure is released, blood flow is quickly resumed and plantar perfusion returns to a normal state. Both (i) and (ii) can be can be reproduced on 20 subjects. We also notice that the contrast of MPI between two feet during the blocking stage is relatively stable across different subjects (see Fig. 3). This again verifies the effectiveness of plantar perfusion imaging as a metric for indicating LLAB.

The statistical analysis of plantar MPI of both feet obtained on 20 subjects during three stages is shown in Fig. 4. For the right foot, the MPI has no significant changes through three stages. For the left foot (with cuff pressure), there is a clear change in the MPI across the three stages, with a significant drop from the preparation stage to the blocking stage, and a significant increase from the blocking stage to the recovery stage. Although the trends of changes are consistent across individuals, the magnitude of their changes varies, which may due to different skin pulsatilities of individuals. As can be seen in Fig. 4(c), the MPI contrast between the left and right foot in the preparation and recovery stages are not significant, but appears to be significant in the blocking stage. The rationale of this is similar to the temperature-contrast-based PAD detection for diabetic foot, where arterial blockage in the lower limbs cause a bad blood circulation in the foot, leading to a difference of temperature between two feet. A similar synergy can be found in our study, i.e. LLAB may lead to a contrast of pulsatile amplitude at two feet. This suggests that LLAB could be detected by analyzing the difference of skin perfusion between the left and right foot.

In summary, LLAB has a significant effect on plantar perfusion. The results suggest a strong correlation between plantar perfusion and LLAB. This implies that the PI generated by the plantar PPG-signal could be a useful indicator for detecting LLAB. Therefore, we propose to further explore the novel concept of using camera-PPG for plantar perfusion imaging and extend the proof-of-concept study to clinical trials, i.e. in the Department of Endocrinology, to include PAD patients (e.g. diabetic patients), and further investigate the feasibility of using camera-PPG based plantar perfusion imaging for PAD diagnosis.

IV. CONCLUSIONS

This is a pilot study that investigates the new concept of using camera-based plantar perfusion imaging to detect LLAB. This may spark new ideas and methods for more convenient and ubiquitous ways for diagnosing PAD. In this work, we successfully constructed a perfusion map based on plantar PPG signals exploiting the advantage of spatial redundancy of an image sensor. Preliminary experimental results show that plantar perfusion is an effective metric

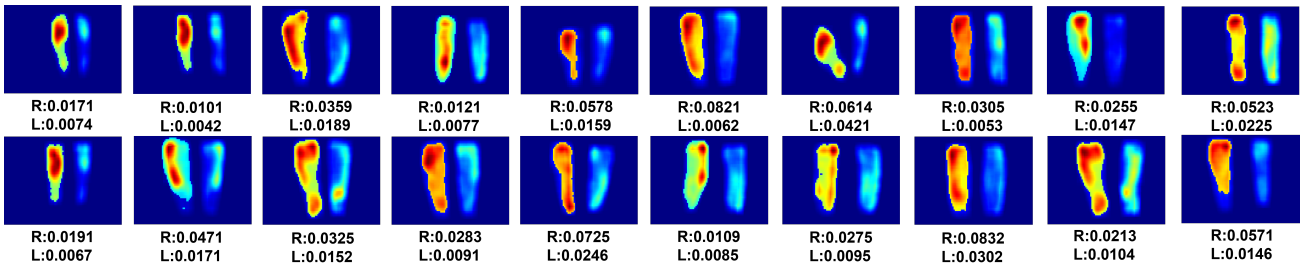
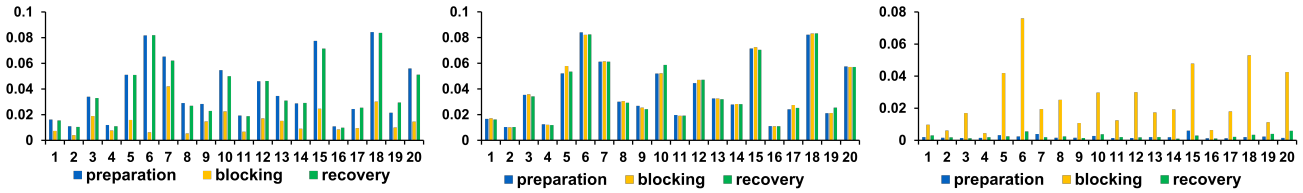


Fig. 3. Blood perfusion map in the feet of 20 subjects during the blocking stage. R indicates MPI of the right foot, L indicates MPI of the left foot.



(a) Left foot (b) Right foot (c) The difference between two feet

Fig. 4. The MPI of of both feet at three different stages. (a) and (b) show MPI values of the left and right foot respectively, (c) shows the absolute difference of PI between the left and right foot to indicate the contrast of PI in the blocking stage.

for recognizing LLAB. This suggests that plantar perfusion imaging has a clear potential in the application of early-diagnosis of PAD. A possible relationship between plantar PI and LLAB has been argued, however, our current study has not yet quantified the relationship utilizing medical devices, nor developed a model to build the relations in between for diagnostic purpose. In the future work, we will benchmark plantar perfusion index (PI) against medical references and validates on patients with PAD. We will also explore the opportunities of generating other physiological maps in addition to the pulsatile map sensed by a camera sensor, such as SpO2, pulse transit time, blood pressure, etc., to establish the fundamentals for LLAB detection.

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