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Evaluation of a non-contact Photo-Plethysmographic Imaging (iPPG) system for peripheral arterial disease assessment

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ABSTRACT

The flow of blood, or perfusion, of the skin can be indicative for the local and also systemic health of an individual. Peripheral Artery Diseases (PAD) are caused by the occlusions of arteries in the peripheral locations of the circulatory system. The high impairment of the patients and the high hospitalization rate of this disease make early diagnosis crucial. The severity of PAD is usually assessed using the Ankle Brachial Index (ABI) and the Ultrasound Doppler technique, which are considered as the gold standard in current clinical practice. Non-contact Photoplethysmography (PPG) imaging is a recent emerging technology capable of monitoring skin perfusion. Using an off-the-shelf camera and a light source, is possible to remotely detect the dynamic changes in blood volume in the skin and derive a map correlated to the blood perfusion. The aim of this study is the evaluation of a PPG imaging system (iPPG) for the assessment of Peripheral Arterial Diseases. Reduced blood flow is simulated on 21 volunteers by increasing the pressure in a pressure cuff. For each volunteer, measurements with iPPG, ultrasound, Laser Speckle Contrast Analysis (LASCA) and ABI were acquired, both on the hand and foot. Our experiments show that iPPG can detect reduced perfusion levels, and correlates well with the other measurement systems, suggesting that iPPG imaging is a valuable alternative to the other gold standard technologies for monitoring PAD. The proposed iPPG has the potential of providing a real-time feedback to the surgeons after resolving vessel stenosis.

Keywords: non-contact PPG, PPG imaging, perfusion, perfusion monitoring, iPPG, Peripheral Arterial Disease, Percutaneous Transluminal Angioplasty, Ankle Brachial Index, ABI.

1. INTRODUCTION

Perfusion is defined as the average rate of blood flow through a capillary bed[1] and can be a valuable indicator of injury and disease.[2] Identifying and quantifying significant changes in perfusion enables several clinical assessments, such as the progress of healing of either burned skin or wounds, tissue necrosis (e.g., foot ulceration, sepsis) and even low-level perfusion assessment. Peripheral Artery Diseases (PAD) are caused by the occlusions of arteries in the peripheral locations of the circulatory system.[3] Plaques build up in the arteries and can harden over time and narrow the arteries. This limits the flow of oxygen-rich blood to organs and other parts of the body. These conditions lead to a high rate of hospitalization and can cause pain during exercises, and, in the most severe stages, pain while resting. These two conditions are called Intermittent Claudication (IC) and Chronic Limb Threatening Ischemia (CLTI), respectively. In some cases, the reduced blood flow in the peripheral limb can cause the loss of tissue and amputation may be needed to prevent necrosis. PAD usually appears after the age of 50 years, with an exponential increase after the age of 65 years.[4] Smoking, hypertension and diabetes are high risk factors for PAD. In case both a healthy lifestyle and a pharmacological treatment do not solve or reduce the level of PAD, a surgical approach is chosen. Percutaneous Transluminal Angioplasty (PTA) is a

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procedure that enables reopening a blocked blood vessel by inflating a balloon located at the extremity of an inserted catheter. When the catheter is in place, it inflates to open the blood vessel, or artery, so that normal blood flow is restored. The high impairment of the patients and the high hospitalization rate of this disease (89.5/100,000 in USA) make an early PAD diagnosis crucial.[5] The severity of PAD is usually assessed using the Ankle Brachial Index (ABI) and the ultrasound Doppler technique, considered as the gold standard in current clinical practice.[6] An emerging third alternative may be represented by the non-contact photoplethysmography (PPG) imaging, which is worthy of further exploration because of its relative simplicity.[7,8] Unlike standard PPG[9,10] that requires skin contact with an optical sensor thereby necessitating a pinpoint area of evaluation, non-contact PPG utilizes an off-the-shelf camera and a light source to remotely detect the dynamic changes in blood volume beneath the skin and then derive a map correlated to the blood perfusion.[11,12] Various algorithms have been proposed for contactless PPG measurements, where most of these aim to substitute contact PPG, measuring vital sign parameters.[13,14] To the best of our knowledge, this is the first work that evaluates iPPG for assessing PAD.

The aim of this study is the evaluation of a Photoplethysmographic imaging system (iPPG) for the assessment of Peripheral Arterial Diseases. Reduced blood flow is simulated on 21 volunteers by inflating a pressure cuff around the limb. On each volunteer, measurements with iPPG, ultrasound, laser speckle contrast analysis (LASCA) and ABI are acquired, both on the hand and on the foot. The measurements acquired using iPPG are compared with the other perfusion monitoring systems.

2. METHOD

2.1 PPG imaging setup and algorithm

The PPG imaging is a technology that utilizes an off-the-shelf camera and a light source to remotely detect the dynamic changes in blood volume beneath the skin (Figure 1a). Our PPG imaging setup is composed of a 2-Megapixels camera equipped with a band-pass Gaussian filter centered at 550 nm, and a LED ring equipped with a cross-polarized light filter. The filter allows removing the specular reflection, namely the light component that is directly reflected and does not interact with the tissue, and allows only the diffuse reflectance reach the camera sensor, namely the light component that does interact with the tissue. Videos of the subjects are acquired at the resolution of 1200×1200 pixels, frame rate of 25 fps for 15 seconds with an exposure time of 40 ms. Videos are saved in a lossless video format. A number of algorithms are used to extract a PPG perfusion map from the acquired videos. The Kanade-Lucas-Tomasi (KLT) algorithm for motion stabilization is employed for compensating human motion, such that the region of interest (ROI) is stabilized and each pixel always corresponds to the same skin location. Subsequent extraction of the PPG signal requires low-pass filtering of each video frame by convolution with a square kernel of 5×5 pixels, to increase the signal-to-noise-ratio (SNR). Then, we normalize the pulsatile component (AC) of the signal of each pixel with respect to its baseline component (DC). This normalization expresses the amplitude of the PPG signal as a percentage, as specified by:

$$PPG_{\text{norm}} = \frac{PPG_{\text{AC}}}{PPG_{\text{DC}}} - 1. \tag{1}$$

This compensates for the parameters that affect both AC and DC signal components, such as intensity of the incident light or skin tone of the subject. The baseline DC component comprises frequencies up to 0.5 Hz, whereas the pulsatile AC component comprises frequencies within the range 0.5-10 Hz.

The perfusion map represents the amplitude of the PPG signal per pixel. To extract the amplitude that corresponds to the PPG modulation, we have adopted the Lock-In amplification method, described in the block diagram of Figure 1b.[8,11] The heart-rate frequency is extracted from the PPG signal obtained by averaging all pixel values of the recorded region of interest (ROI, Figure 1c). The heart-rate frequency is defined as the dominant frequency peak of the PPG signal, therefore assuming that the heart rate stays constant for the entire time of the video acquisition (15 seconds). Afterwards, a complex reference signal $R(t)$ is defined, of which a cosine waveform modulated at the heart-rate frequency represents its real part, and a sine waveform modulated as well at the heart-rate frequency represents its imaginary part. The signal $R(t)$ is used to extract the amplitude of the PPG signal from each pixel and is described by:

$$R(t) = cos(\omega_{HR}t) + jsin(\omega_{HR}t). \tag{2}$$

Instead, the signal $S(t)$ is the local PPG signal extracted from a single pixel, with amplitude A of the modulating heart-rate frequency, the phase shift ϕ of the signal $S(t)$ with respect to the reference $R(t)$, and $S_n(t)$ which contains all the other frequency components and the noise, which results in:

$$S(t) = Acos(\omega_{HR}t + \phi) + S_n(t). \tag{3}$$

The signal $S(t)$ is multiplied by $R(t)$ in order to obtain the signal $H(t)$. By averaging $H(t)$ over time we obtain the steady complex component H, with real part x and imaginary part y, correlated to the amplitude A and the phase ϕ, giving:

$$H = x + jy; \qquad x = \frac{A}{2}cos(\phi); \qquad y = -\frac{A}{2}sin(\phi). \tag{4}$$

At this point, the components x and y can be combined in order to extract A and ϕ:

$$A = 2\sqrt{(x^2 + y^2)}; \qquad \phi = atan(-\frac{y}{x}). \tag{5}$$

By extracting the amplitude A from the PPG signal of each pixel of the video, a PPG amplitude map is created. The perfusion of the obtained PPG map is color-coded, where blue indicates low perfusion and red indicates high perfusion (Figure 1d). Instead, by extracting the phase ϕ from the PPG signal of each pixel of the video, a PPG phase map is created (Figure 1e). The phase provides a measure of the time delay between the PPG signal wave of each pixel and the reference PPG signal $R(t)$. The phase can be converted in seconds of delay by using:

$$\text{Delay}[s] = \frac{\phi[\text{degrees}]}{360[\text{degrees}]} \times \frac{1}{\text{Heart Rate [Hz]}}, \tag{6}$$

but for the data processing, we only refer at phase in degrees. Since the reference $R(t)$ signal is extracted from the entire ROI, a PPG signal from a given location of the image is likely to be in phase with the reference. Similar to the map of the amplitude, also for the map of the phase each value of the map is color-coded. The HSV color system is employed, since it works well with the phase map that ranges within $\pm 180°$, and the color that corresponds to the higher value is the same as the color of the lower value, as in a continuous loop.

2.2 Other methods used for perfusion assessment

Besides the PPG imaging system, other instruments also monitor the perfusion and are depicted in Figure 2 and briefly discussed now. In the diagnostic process, the Ankle Brachial Index (ABI) is the first milestone suggested by all the guidelines for assessing PAD. In this study, the MESI-ABPI instrument (MESI, Slovenia) for measuring the ABI was used (Fig. 2a). Three pressure cuffs are inflated, one on the right arm and the other two on both legs of the volunteer. The test compares the systolic pressure at the arm with the systolic pressure reached in the two legs. Then an index R, defined as the ratio between the pressure at the foot and the pressure at the arm, is computed. When the index R is between 1.00 and 1.40, no blockage is detected. In this range, the subject shows a similar pressure recorded on the upper and lower limb, suggesting that there are no stenosis in the lower limb. An index value between 0.91 and 1.00 indicates a borderline condition, whereas an index value below 0.90 suggests a reduced flow in the lower limb, resulting in the first evidence of PAD. If the ABI is higher than 1.4 the hypothesis refers to uncompressible arteries in the lower limbs. This result may be caused by arteriosclerotic pathologies and diabetes. Patients with these diseases show stiffened ankle arteries that may limit the predictive value of the ABI, a limitation that may be overcome by measurement of the Toe-Brachial Index.

The Ultrasound (US) in duplex mode is a technique (Fig. 2b) that allows the visualization of the vessel and the estimation of the blood velocity.[15] The measures are recorded with the US on the radial artery and on the anterior tibial artery. Duplex US merges the anatomical information generated by the US imaging system with the functional information generated by the Doppler measurement of the blood flow velocity. The US measurement of the velocity can be recorded exploiting the Doppler effect: if the flow is moving in the same direction of the stimulation and reading of the transducer in the probe, the velocity of the flow can be estimated. In this project, we used the EPIQ 7 Ultrasound Machine associated with an eL18-4 PureWave transducer (Philips Medical Systems, The Netherlands). At the bottom part of the screen, the Pulsed Wave Doppler (PW) is displayed, which represents the velocity of the flow measured at the gate. The sign of the velocity wave is determined by

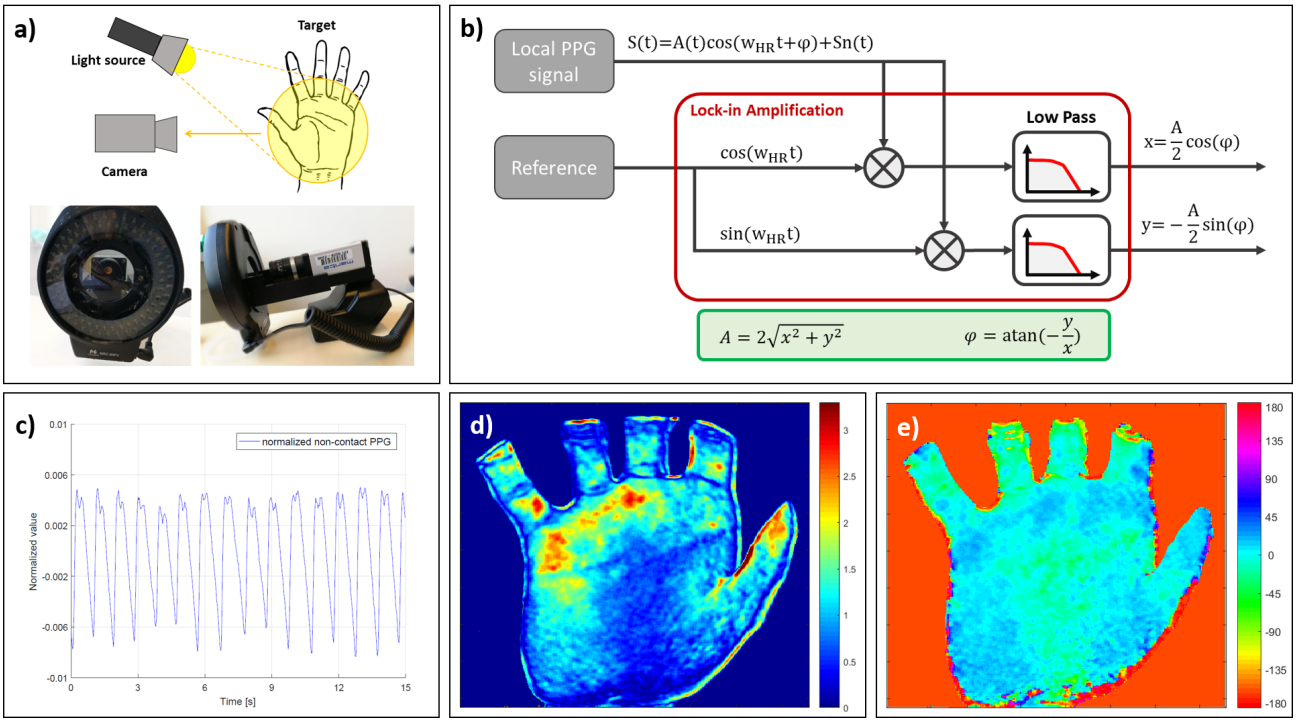

Figure 1. a) Setup for PPG imaging acquisition, composed of a camera and a light source. b) Block diagram of the Lock-In amplification algorithm for extracting the perfusion map. c) Normalized PPG signal from the entire region of interest. d) PPG Amplitude map. e) PPG phase map.

the relative direction of the probe and the flow. The intensity of the velocity is color-coded: the color red is associated with a high velocity towards flow, while the color blue is associated to the blood flowing away from the probe. The velocity data were acquired with a sampling rate of 250 Hz for approximately 10 seconds.

The Laser Speckle Contrast Analysis, or LASCA (Fig. 2c), is a technology that exploits a random interference effect that gives a grainy appearance to objects illuminated by a laser light diverged with a lens.[16,17] In the case of light scattered from a large number of individual moving scatterers, such as particles in a fluid like blood, the speckle pattern fluctuates. The fluctuations provide information about the velocity distribution of the scatterers. A map of the velocity distribution is produced by evaluating the local contrast of the speckle pattern, computed as the ratio between the standard deviation σ of a local subset of pixels and their mean intensity I. Local contrast is inversely proportional to fluid velocity. As the velocity of blood flow increases, there are faster fluctuations and more averaging occurs in a given integration time, leading to a decrease of the local contrast. Local contrast is color-coded, with red indicating lower contrast and blue indicating higher contrast. The system used for the LASCA measurements was the PeriCam PSI NR (Perimed, Sweden). The PeriCam PSI system uses an invisible near infra-red (NIR) laser (785 nm). The beam is spread over the measurement area by a diffuser, creating the speckle pattern. The size of the illuminated area depends on the distance between the laser aperture in the head and the measurement object. The speckle pattern is recorded via a 1388 × 1038-pixel CCD sensor, capable of recording at 100 fps. For these experiments, we use a frame rate of 21 fps, thus to have measurements comparable with iPPG. The duration of the measurements was 20 seconds. The PeriCam is attached to a passive robotic arm, anchored to the operator desk.

In addition, the Intellivue MP50 (Philips Medical Systems, The Netherlands) with an RD SET DCI Adult SpO2 reusable sensor (Masimo, The Netherlands), was used continuously (Fig. 2d) during the experiments for monitoring the vital signs of the volunteers. The sensor was attached onto the toe of the right foot. Data was streamed from the MP50 to the PC via a serial port, through an RJ45-to-USB converter cable. SpO2 and heart rate were saved, as well as the PPG signal sampled at 125 Hz. Figure 3 lists a summary of all the used technologies.

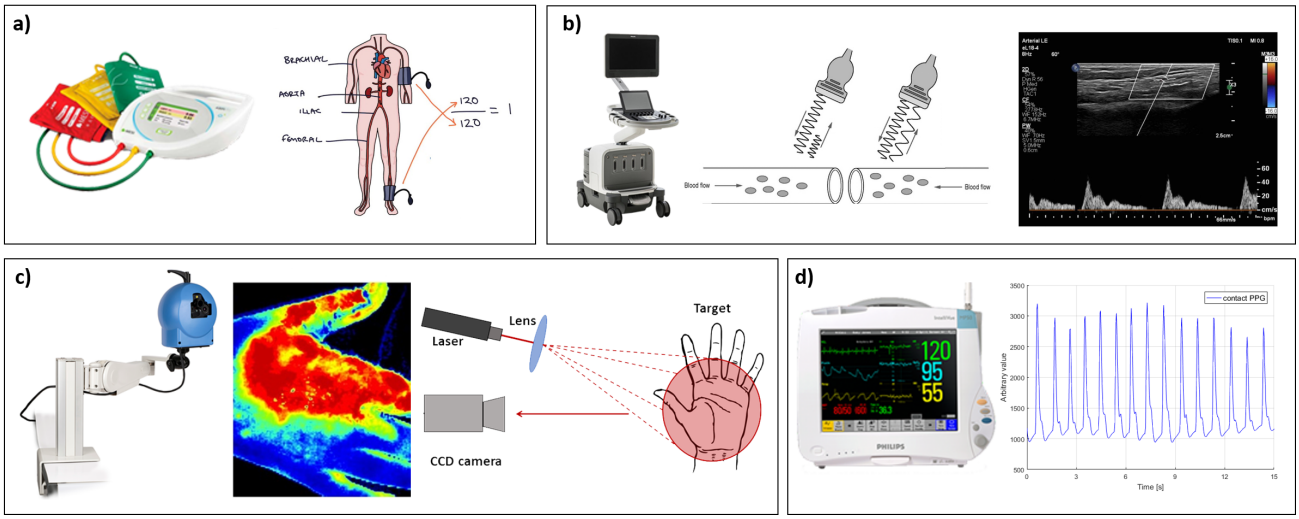

Figure 2. Perfusion monitoring systems: a) MESI-ABPI for the ABI index. b) Ultrasound console for US in Duplex mode. c) Perimed system for LASCA measurements. d) The Intellivue MP50 system for heart-rate monitoring.

Name	Technology concept	Perfusion	Pressure	Non-contact	Image	Heart rate	Disadvantage
Imaging PPG	Blood pulsatility from video pixels brightness	●		●	●	●	Sensitive to motion
Ultrasound (Duplex mode)	Doppler measurement of the blood flow velocity	●			●	●	Operator dependent
LASCA	Speckle interference pattern correlated with blood scatterers	●		●	●	●	Very sensitive to motion
ABI	Ratio between systolic pressure at the arm and at the legs		●			●	Not a continuous measurement
Contact PPG	Heart rate measure using a finger clip sensor					●	Punctual information on heart rate

Figure 3. Summary of all the used technologies, with a short description of their advantages and disadvantages.

2.3 Description of the experiments

Experiments on 21 volunteers were carried out to simulate the condition of reduced blood flow in the upper and lower limb. Volunteers were equally distributed in gender and age groups. Experiments were conducted on 10 males and 11 females, from three age groups: six volunteers with age between 18 and 35, eight with age between 35 and 55, and seven volunteers with age from 55 to 75. Among all volunteers, four have known cardiovascular problems, but do not know which disease for privacy reasons. The only exclusion criterion for the selection of volunteers was diabetes, since this disease causes calcification of arteries and their consequent stiffening, in particular at the ankle level. This makes the artificial occlusion of the artery more difficult. This phenomenon may lead to the recording of a high ABI index, even when the perfusion in the foot is very low, with consequent underdiagnoses of PAD in diabetic patients. Four of the volunteers have also known previous diseases related to the cardiovascular and circulatory system. The nature of the diseases is not known thus to protect the privacy of the subjects.

The experimental protocol was explained to each volunteer, prior to signing the informed consent. Lights were switched-off during the measurements, to reduce the interferences with the iPPG and LASCA systems and to make the volunteer more comfortable (Figure 4). A contact PPG probe was attached to the toe of the volunteer, in order to monitor the heart rate during the entire experiment. During the experiments, the volunteer was situated on the table in a supine position and deflated cuffs were placed around their arms and legs. At

the beginning of the experiments, the temperature was measured on the hand and foot of the volunteers, and an ABI measurement was performed. The ABI indexes of both legs were recorded, as well as heart rate and systolic and diastolic pressure. Then perfusion was monitored on hand and foot of the subject with iPPG, US and LASCA, at five different stages of pressure. The first stage, called baseline, was measured with no cuffs inflated. Then, according to the systolic pressure of the volunteer measured with the ABI, pressure cuffs were inflated around the arm and leg at 40%, 80% and 120% of the systolic pressure. Cuff pressure for these three mentioned stages was set using the ABI. The last stage, called deflated, was measured after deflating completely the cuff, and waiting three minutes in order to restore the proper blood flow of the limb. In each of these five stages, a) measurements with US in duplex mode were acquired on the radial artery and on the tibial anterior artery, b) iPPG measurements were acquired on both hand and foot, while c) LASCA was acquired only on the foot, since the instrument was anchored to a table and it was difficult to move it around the volunteer. The measures of US during the 120%-inflated situation was not possible on the hand, since blood flow in the arm was absent. Two consecutive measurements with each device were acquired for each stage. The measurements with iPPG during the baseline were simultaneously acquired from the hand and from the foot, since two identical iPPG setups were used. Simultaneous acquisitions during the inflated situations were not possible, since the ABI was able to inflate only one cuff at the time. At the end of the experiments, the ABI measure was repeated and the temperature on the hand, foot and the room were measured again.

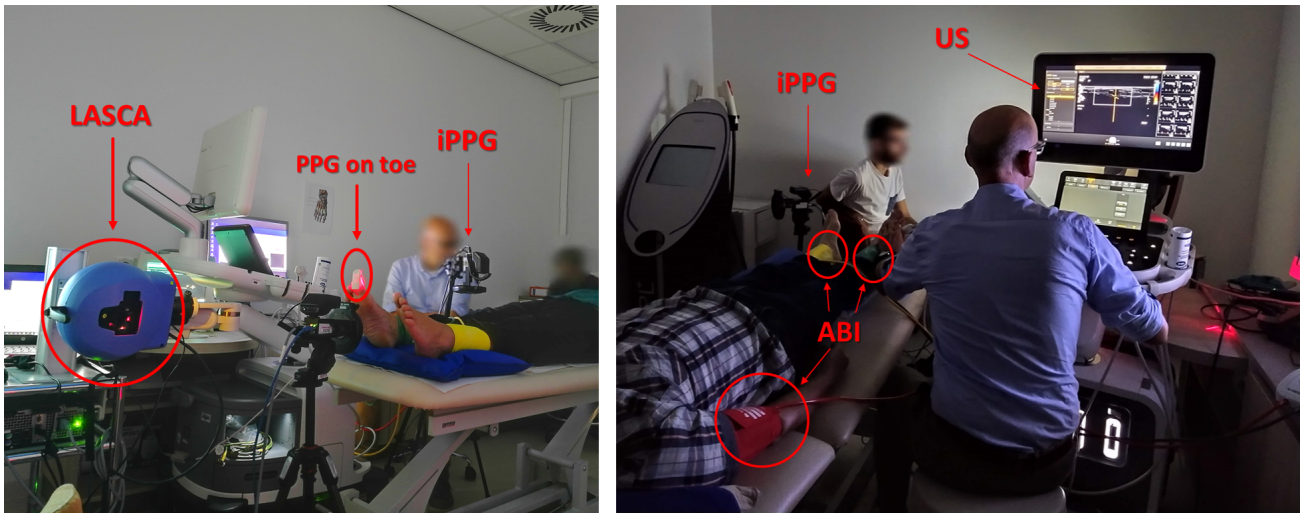

Figure 4. Setup of the experiments. The volunteer lies on the bed, cuffs are positioned around their arm and legs. All the used measurements devices are displaced around and indicated.

3. RESULTS

The data gathered from the 21 subjects were processed in order to assess the change in perfusion, resulting from the applied pressure on the limbs using the cuffs. Heart rate was extracted from each instrument used and then compared with the reference heart rate measured with the MP50 monitor. Several 95% Confidence Interval plots were created and populated, for each used technique, with data coming from the 5 different stages of pressure discussed above, namely baseline, 40%, 80%, 120% of systolic pressure and finally the deflated stage.

3.1 Heart-rate analysis

The heart rate of the volunteers is extracted from each instrument and compared with the one measured by the MP50 monitor, which is used as a reference. The heart rate is a vital indicator that can be extracted from each measured signal, and can be therefore used as a first way for removing measurements affected by noise. The heart rate is extracted from the PPG imaging signal, which is obtained by averaging all the pixel values of the recorded ROI of the video. For the LASCA, a similar approach to the PPG imaging is used, extracting

the dominant frequency peak of the signal of perfusion. Instead, for the US measurements the heart rate is extracted from the peak-to-peak distance of the velocity profile in the time domain, following the same principles used for the Pan-Tompkins algorithm for the heart-rate estimation from the ECG signal. The plots of the 95% Confidence Interval of Figure 5 show the differences between the heart rate computed by each instrument and the heart rate measured by the MP50 monitor. The iPPG is the technology that performs better, with a mean difference of -1 bpm. It should be noticed that the foot where the sensor was located was not blocked during the experiments, this adds an additional error to the measure.

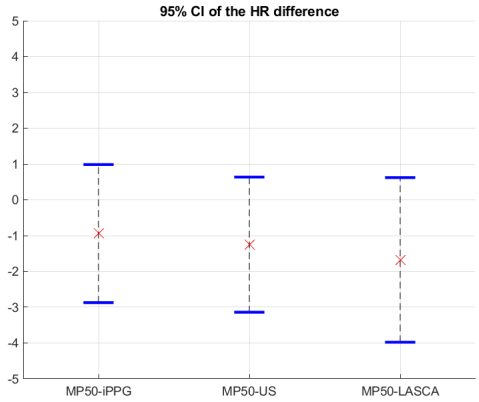

Figure 5. Plot of the 95% Confidence Interval of the difference between the heart rate measured by the MP50 and the heart rate measured by the instruments.

3.2 PPG imaging

From the PPG data, plots of the 95% Confidence Interval were created from the PPG signal averaged from the entire ROI. The pulsatility AC of the average PPG signal is first normalized with respect with its DC component, expressing the amplitude of the PPG signal as a percentage, according to Equation (1). Figure 6 shows the plots of the 95% Confidence Interval related to the amplitude of the iPPG signal extracted from the entire ROI, from hand and foot, respectively. The plots show that the power of the PPG signal decreases from the baseline condition as the pressure of the cuff increases, and then the power of the signal increases again in the deflated stage almost to the same level as the baseline level.

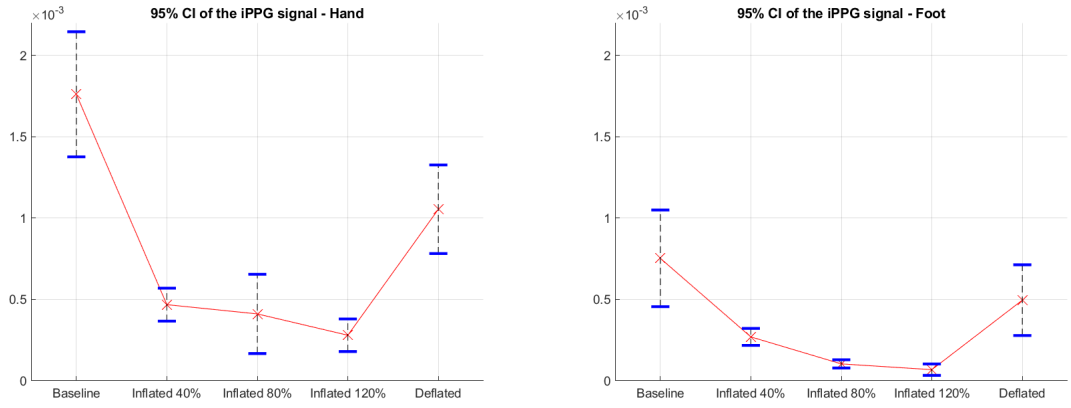

Figure 6. Plot of the 95% Confidence Interval of the amplitude of the iPPG signal during the different inflation stages of the experiments on both hand and foot.

The plots of the 95% Confidence Interval were created for the PPG maps as well. The PPG maps are images that represent the 2D distribution of perfusion of the ROI and, in order to populate the plots, a single representative value for each image is considered. For the PPG amplitude maps, the median of the amplitude map is used, while the PPG phase maps are based on the inter-quartile range. Figure 7 shows the plots of the 95% Confidence Interval of the PPG amplitude maps for the hand and for the foot. In both cases, the median value of the amplitude map decreases as the pressure of the cuff increases, eventually in the deflated stage the amplitude comes back almost to the baseline level. Figure 8 shows the plots of the 95% Confidence Interval of the inter-quartile range of the PPG phase maps for the hand and for the foot. In this case, the inter-quartile range of the phase maps augments as the pressure inside the cuff increases, and then decreases again in the deflated stage. This behavior can be observed in both the hand and foot measurements.

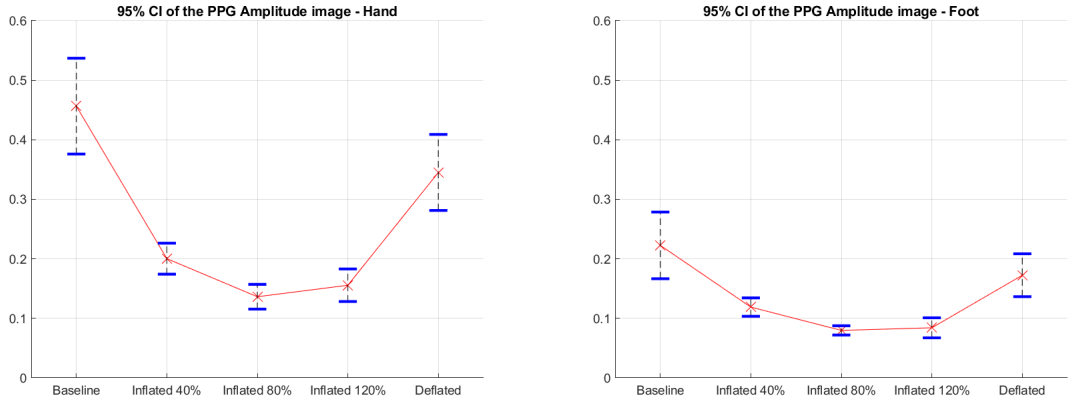

Figure 7. Plot of the 95% Confidence Interval of median value of the amplitude maps during the different inflation stages of the experiments on both and and foot.

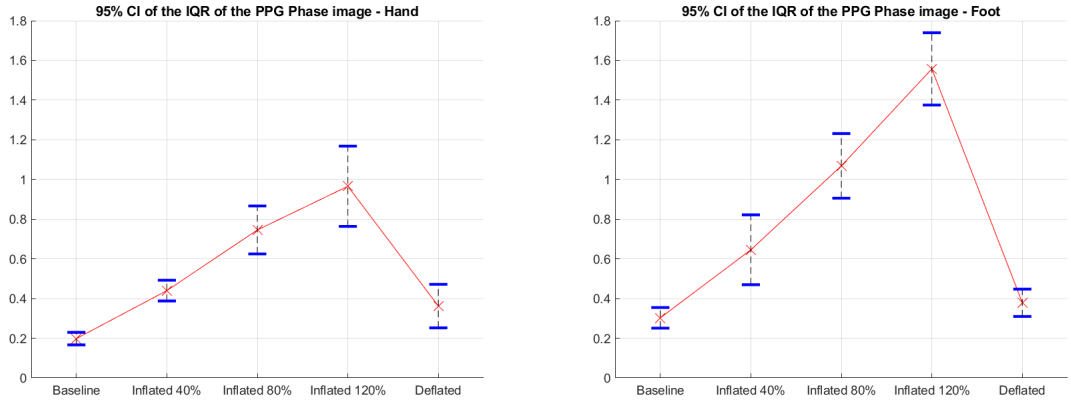

Figure 8. Plot of the 95% Confidence Interval of the inter-quartile range of the phase maps during the different inflation stages of the experiments on both and and foot.

3.3 Ultrasound

From the US data, the velocity envelope was extracted and a cumulative measure, the Average Volume Density (AVD), was used for populating the plots. The AVD is defined as the integral of the velocity profile during the measure and represents the amount of blood that passes through the area scanned with the probe, with

the assumption that the area is constant during the measurement. This is only a coarse approximation for the anterior tibial artery and for the radial artery, but can be considered as a normalization for the variability of the diameter of the vessels in the population. Figure 9 shows the plots of the 95% Confidence Interval populated with the AVD extracted from the US measurements. It can be noticed that by increasing the pressure in the external cuffs, the AVD decreases with respect to the baseline. This effect is more evident in the arm rather than in the leg.

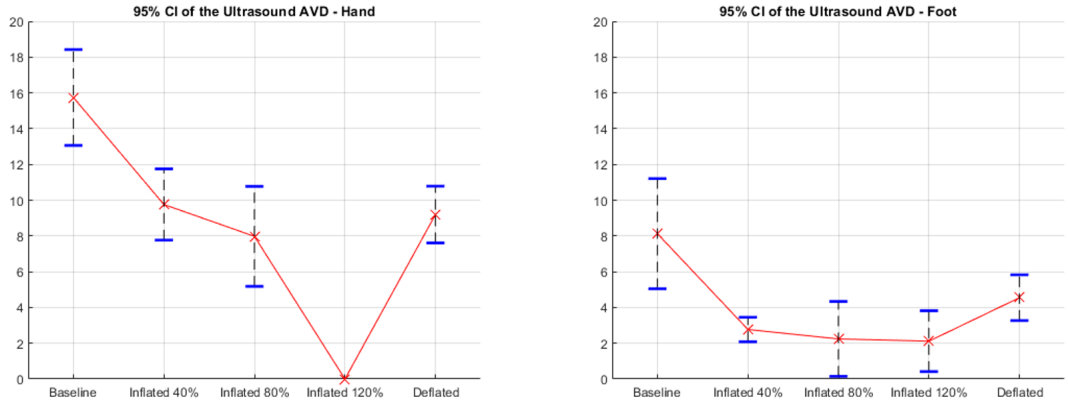

Figure 9. Plot of the 95% Confidence Interval of the Average Volume Density (AVD) during the different inflation stages of the experiments on both hand and foot.

3.4 LASCA

Also for the LASCA measurements, similar to the PPG amplitude maps, the median value was used to represent an entire perfusion image. Figure 10 depicts the plots of the 95% Confidence Interval related to the LASCA measurement from the foot. In this case, the perfusion decreases as the pressure of the cuff increases in the 40% and in the 80% stages, but starts increasing again in the 120% stage and comes back almost to the baseline level in the deflated stage.

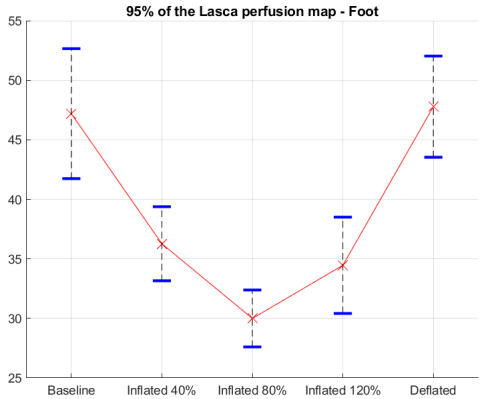

Figure 10. Plot of the 95% Confidence Interval of the LASCA perfusion measurements during the different inflation stages of the foot experiments.

4. DISCUSSION

The heart-rate analysis shows a good correlation between the MP50 reference signal and the other instruments used for measurements. The amplitude of iPPG maps and average iPPG signal, US and LASCA show a similar behavior across the five different stages of perfusion. As the pressure of the cuffs gradually increase until they exceed the systolic pressure, all the technologies show the gradual decrease of the detected perfusion. Different considerations can be made for the plots related to the inter-quartile ranges of the iPPG phase maps. Conversely to what the other plots show, when the pressure of the cuffs gradually increase until they exceed the systolic pressure, the inter-quartile ranges of the phase map increase. This is explained by the fact that, when the pressure of the cuffs increase, PPG pulsation in each pixel decreases and PPG signals appear less coherent among each other, therefore increasing the distribution of the phase values of the map.

For both iPPG and US, the measurements taken on the hands show a larger amplitude of the signal with respect to the measurements taken on the foot, for all the five stages. A comparison between hand and foot for LASCA is not possible, since only measurements on the foot were taken. The PeriCam system was fixated to a table and it was difficult to move around for measurements on both foot and hand. No US measurements were taken on the hand at 120% of the systolic pressure. The pressure on the cuff completely blocks the blood flow downstream, therefore no signal is detected on the radial artery. Instead, on the foot, US measurement can still be taken at 120% of the systolic pressure. The pressure is applied on the leg, and the bones of tibia and fibula prevent all the arteries to close completely. In the case of LASCA at 120% of the systolic pressure, the monitored perfusion increases. This can be explained by considering that the noise overtakes the measurement signal, so that they cannot be discerned anymore. In the deflated stage of all the instruments, the value of perfusion does not return to the baseline level. This may be due to the fact that some physiological adjustments of the perfusion take place as an external pressure is applied to a limb. The deflated stage was acquired waiting 3 minutes after the 120% stage and this period of time may not be long enough for ensuring a complete restoration of the blood flow. The inter-quartile range of these plots show a high variability. All the measurements were taken on free hands and feet, where volunteers were asked to hold their hand and foot position during the measurements, but some overall motion could potentially occur when cuffs were inflated. Many subjects also experienced some discomfort while cuffs were inflated.

The experiments show that the PPG imaging is able to detect the reduced perfusion, due to the external pressure applied via the cuffs around the limbs. These results correlate well with the other used technologies, namely US and LASCA, and suggest that non-contact PPG imaging is a valuable alternative to the other technologies for monitoring PAD. Furthermore, PPG presents several advantages with respect to the others. PPG imaging allows the remote monitoring of the perfusion, while for the US an experienced operator needs to hold the probe in position, which must always stay in contact with the patient. PPG imaging also allows to build a spatial map of perfusion, which helps in detecting areas with reduced blood flow. With respect to LASCA, PPG imaging is also more robust against motion. The pulsatility information is encoded in the color changes of the pixels, and algorithms for motion stabilization can be implemented on iPPG videos. The reduction in contrast of the speckle pattern is due both to the motion of the body part and to the motion of the blood in the capillary bed, which behaves as moving scatterers. Since the interest is in the blood-flow velocity, body-part motion represents one of the main issues of the laser-speckle technology. One possible application of the iPPG system can involve its use during Percutaneous Transluminal Angioplasty (PTA), thus to provide a real-time feedback to the surgeon on the status of the perfusion after resolving the stenosis in the vessel.

5. CONCLUSIONS

In this study, we have evaluated an imaging photoplethysmographic system (iPPG) for the assessment of peripheral arterial diseases (PAD). Reduced blood flow was simulated on 21 volunteers using a cuff for pressure measurements. To the best of our knowledge, this is the first time that PPG imaging is evaluated for the assessment of PAD. On each volunteer, measurements with iPPG, US, LASCA and ABI were acquired, both on the hand and on the foot. The experiments show that iPPG can detect reduced perfusion levels, and correlates well with the other measurement systems, suggesting that non-contact PPG imaging is a valuable alternative to the other technologies for PAD monitoring. Furthermore, it has the potential of providing a real-time feedback to surgeons after resolving vessel stenosis.

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