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Original Article

The Correlation Between Finger Mean Arterial Pressure and Blood Pressure Measurement

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Abstract *- Blood Pressure (BP), a vital indicator, is influenced by the pressure exerted by blood against the walls of arteries, playing a fundamental role in health assessment. A non-invasive optical method, Photoplethysmography (PPG), is utilized for measuring changes in blood volume per heartbeat, reflecting the mechanical action of the heart. Given the inherent connection between PPG signals and heart contractions, it is reasonable to investigate the potential correlation between PPG signals and blood pressure measurements. In this study, a statistical analysis is conducted with the aim of establishing the relationship between PPG signals and blood pressure. Specifically, the study focuses on Finger Mean Arterial Pressure (MAP), derived from the PPG signal, aiming to be statistically compared with various blood pressure components, including Systolic Blood Pressure (SBP), Diastolic Blood Pressure (DBP), and Brachial Blood Pressure. The objective of this analysis is to shed light on the potential associations and clinical relevance between PPG signals and blood pressure parameters. The estimation of SBP and DBP involved a non-real-time measurement method, requiring the consensus of two experts who resolved any disparities in their assessments. This comprehensive analysis provides a deeper understanding of the potential connections between PPG signals and blood pressure, shedding light on their interplay and clinical relevance. Brachial MAP is obtained from the oscillometric signal. The data is collected from a group of 30 healthy individuals, and Pearson's correlation coefficients are calculated to determine the associations between finger MAP and SBP, DBP, and brachial MAP. The mean differences between the systolic and diastolic measurements by the two experts are -2.63 ± 1.90 and -3.12 ± 2.51 mmHg, respectively. The correlation coefficients for finger MAP versus brachial MAP, finger MAP versus systolic pressure, and finger MAP versus diastolic pressure are 0.9820, 0.8591, and 0.7915, respectively. Based on these findings, a strong connection between finger MAP and blood pressure is suggested, offering potential opportunities to derive SBP and DBP using the PPG signal through finger MAP.*

Keywords *- Blood Pressure, Photoplethysmography, Mean arterial pressure, Oscillometric.*

1. Introduction

The importance of accurate and non-invasive blood pressure measurement in healthcare settings is underscored, as vital information for diagnosing and managing various cardiovascular conditions is provided by it. Traditional blood pressure measurement techniques involving using a cuff around the upper arm can be uncomfortable and cumbersome for patients. Therefore, there is a growing interest in exploring alternative methods that offer convenience and reliability.

This study investigates the correlation between finger Mean Arterial Pressure (MAP) and blood pressure measurements to explore the potential use of photoplethysmography (PPG) signals as a non-invasive and cuff-less approach.

PPG is a technique that captures changes in blood volume through the analysis of light absorption and reflection in peripheral tissues, particularly the fingertip. By analyzing PPG signals, it is possible to derive various physiological parameters, including finger MAP. The association between Finger Mean Arterial Pressure (MAP), acquired via PPG analysis, and conventional blood pressure measurements, encompassing Systolic Blood Pressure (SBP), Diastolic Blood Pressure (DBP), and Brachial Mean Arterial Pressure (MAP), is primarily evaluated in this study.

Statistical analysis using the Pearson correlation coefficient was conducted to examine the correlation between finger MAP and blood pressure parameters. A strong correlation between finger MAP and blood pressure measurements was observed in the results of our analysis. This observation suggests that finger MAP, derived from PPG signals, holds promise as a potential indicator for estimating blood pressure.

The significant potential implications of our findings should be noted. If the correlation between Finger Mean Arterial Pressure (MAP) and blood pressure can be validated, the possibility of employing PPG analysis as a non-invasive and cuff-less technique for blood pressure estimation is possible. This could have significant implications for more convenient and accessible blood pressure monitoring in clinical and non-clinical settings. Such an approach would enhance patient comfort and offer opportunities for continuous monitoring in various settings, including home healthcare and wearable devices.

In conclusion, this study explores the correlation between finger MAP obtained from PPG analysis and traditional blood pressure measurements. The strong correlation observed between these variables suggests that PPG signals hold promise as a potential indicator for estimating blood pressure in a non-invasive manner. By establishing this relationship, future research can delve into the development of accurate and convenient methods for blood pressure estimation, ultimately improving healthcare practices and patient outcomes.

2. Blood Pressure

2.1. Blood Pressure Measurement

The measurement of blood pressure is highly significant in assessing cardiovascular health. It plays a crucial role in the early detection, prevention, and management of cardiovascular diseases. Typically, Blood Pressure (BP) is evaluated in the brachial artery located in the upper arm. This artery is the primary site for drawing blood from the heart. During each heartbeat, blood pressure experiences variations, oscillating between its peak value, known as systolic pressure and its lowest value, termed diastolic pressure.

These measurements offer a concise summary of an individual's blood pressure profile. Systolic blood pressure reflects the pressure exerted on the artery walls when the heart contracts and pumps blood. On the other hand, diastolic blood pressure represents the pressure when the heart is at rest between beats.

Analyzing the blood pressure profile yields valuable insights into cardiovascular health. Hypertension, commonly known as high blood pressure, has the potential to cause significant damage to blood vessels, significantly increasing the risk of various complications, such as stroke, heart failure, and kidney disease. Conversely, excessively low blood pressure, or hypotension, can lead to inadequate oxygen and nutrient supply to vital organs, resulting in organ dysfunction.

Blood pressure (BP) measurement methods can be broadly categorized into two main categories: invasive and non-invasive. The invasive method involves inserting a catheter or sensor directly into an artery or blood vessel. It is often used in critical care settings and during certain medical procedures. Invasive BP monitoring provides continuous and highly accurate measurements but is associated with some risks and discomfort for the patient. Meanwhile, the Non-invasive Blood Pressure (NIBP) measurement is more commonly used as it is portable, user-friendly, and reduces patient discomfort. Automated electronic BP devices are popular for NIBP measurements and are increasingly used in various settings [3,4]. Non-invasive BP estimation employs two methods: auscultatory (manual) and oscillometric (automatic) [5,6]. Both methods utilize an arm cuff placed on the upper arm with the artery marker aligned over the brachial artery, which serves as the standard location for BP measurement [7]. The blood pressure measurement procedure entails both the inflation and deflation of the cuff. Initially, pressure is exerted by the cuff wrapped around the upper arm, temporarily occluding blood flow in the brachial artery. Subsequently, this pressure is slowly released by the cuff, allowing the return of pulsatile blood flow. During the deflation phase of the cuff, the intra-arterial pressure within the brachial artery interacts with external pressure from the cuff. This interaction leads to turbulence in the blood flow, giving rise to distinct tapping sounds known as Korotkoff sounds. These sounds are characteristic indicators of the ongoing blood pressure measurement process. These sounds are accompanied by generating an oscillometric signal [8].

The auscultatory method, relying on detecting Korotkoff sounds, is considered the gold standard for Non-invasive Blood Pressure (NIBP) measurement. It has gained widespread acceptance and recognition as such by numerous authoritative sources [9-13] since it was first introduced in 1905 for estimating Systolic Blood Pressure (SBP) and Diastolic Blood Pressure (DBP). To establish the relationship between the cuff, blood flow, SBP, and DBP, the initial step involves inflating the cuff to a pressure level surpassing the SBP. This action completely occludes the artery, leading to the absence of both blood flow and any audible sound during this phase of the measurement process. Gradually, the cuff pressure is reduced (deflated) until it aligns with SBP, allowing blood to commence its flow. The first Korotkoff sound becomes audible at this juncture, and this reading is recorded as the SBP. While blood circulates, Korotkoff sounds persist until their eventual cessation, signifying the DBP. In contrast, the oscillometric method estimates blood pressure by scrutinizing the oscillations in cuff pressure during its gradual deflation from a level surpassing SBP to falling below DBP.

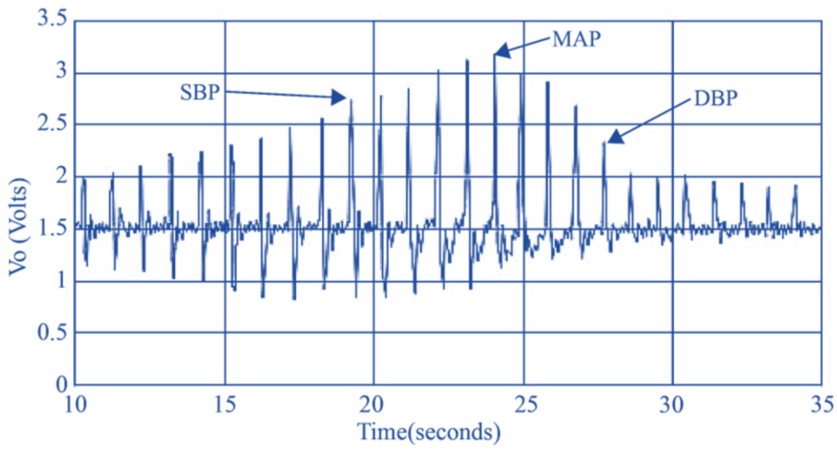

Fig. 1 An example of an oscillometric signal for a blood pressure measurement [16]

During the deflation of a cuff, the amplitude of pressure oscillation is affected by the transduced cuff pressure. Interestingly, the maximum oscillation point has been observed to align with the Mean Arterial Pressure (MAP) or brachial MAP [14,15]. With this understanding, the estimation of Systolic Blood Pressure (SBP) and Diastolic Blood Pressure (DBP) can be achieved by identifying the cuff pressure value at which a specific fraction of the maximum oscillation amplitude is reached in the oscillometric signal. An example of an oscillometric signal illustrating the locations of SBP, DBP, and mean arterial pressure (MAP) is shown in Figure 1.

2.2. Brachial Mean Arterial Pressure (MAP)

Pulse oximetry, a cost-effective and noninvasive tool, holds a pivotal role in the monitoring of oxygen saturation (SaO2) levels. Its effectiveness has been firmly established, earning recognition as the standard noninvasive method for SaO2 measurement since 1987, endorsed by authoritative organizations such as the International Standards Organization and the European Committee for Standardisation [17]. The measurement of SaO2 through pulse oximetry hinges on the principle of photoplethysmography (PPG), which exploits light absorption as it traverses hemoglobin. In this technique, a light-emitting diode emits light that either permeates body tissues, typically the finger or is reflected from them. Subsequently, a photodiode gauges the intensity of the unabsorbed light. During systole, when the heart contracts, there is an augmentation in the volume of arterial blood in the fingertip. Consequently, more light is absorbed as it traverses the tissue, resulting in a reduction in the intensity of the light detected by the photodiode.

Figure 2 provides an illustration of a photoplethysmography (PPG) signal, which is presented as the intensity of light absorption. The PPG signal is closely linked with changes in the volume of arterial blood within the fingertip. Within the PPG signal, prominent peaks align with the highest arterial blood volume during systole (when the heart contracts), while the troughs correspond to the lowest arterial blood volume during end-diastole (when the heart relaxes) [18]. This pulsating aspect of the PPG signal is commonly denoted as the AC component. In contrast, the non-pulsatile portion, which remains stable regardless of variations in arterial blood volume, is referred to as the DC component [19].

2.3. Finger' Mean Arterial Pressure (MAP)

When an additional contact force is exerted between the finger being measured and the pulse oximeter during PPG generation, the amplitude of the AC component, also known as the pulse amplitude, undergoes a specific pattern. Initially, as shown in Figure 3, the pulse amplitude increases and then decreases until it reaches a flattened state [20,21]. The figure demonstrates the simultaneous recording of the PPG and contact force signals. In the first 8 seconds, the AC component is in a normal condition. However, as the contact force gradually increases, the pulse amplitude exhibits an increasing and decreasing trend until the pulsations eventually disappear. The maximum amplitude of the AC component is defined as the finger Mean Arterial Pressure (MAP).

2.4. Brachial MAP vs. Finger MAP

In a general context, transmural pressure denotes the pressure within a compartment in relation to the pressure external to it. When considering static conditions, transmural pressure is synonymous with the elastic recoil pressure of the compartment [22]. In a physiological context, transmural pressure represents the disparity between the pressure inside the blood vessel (intra-arterial pressure) and the external pressure exerted on the blood vessel wall [23]. The intra-arterial and external pressures are balanced when the transmural pressure is zero. This scenario corresponds to the intra-arterial pressure of the brachial and finger blood vessels coinciding with their respective external pressures at the points of brachial Mean Arterial Pressure (MAP) and finger MAP. [24]

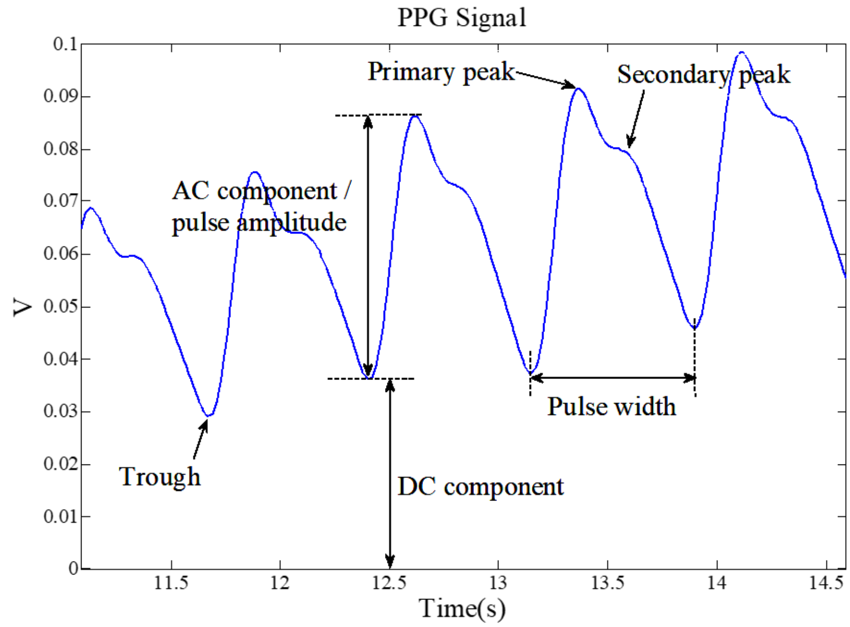

Fig. 2 A typical PPG signal in light absorption intensity corresponds to changes in arterial blood volume

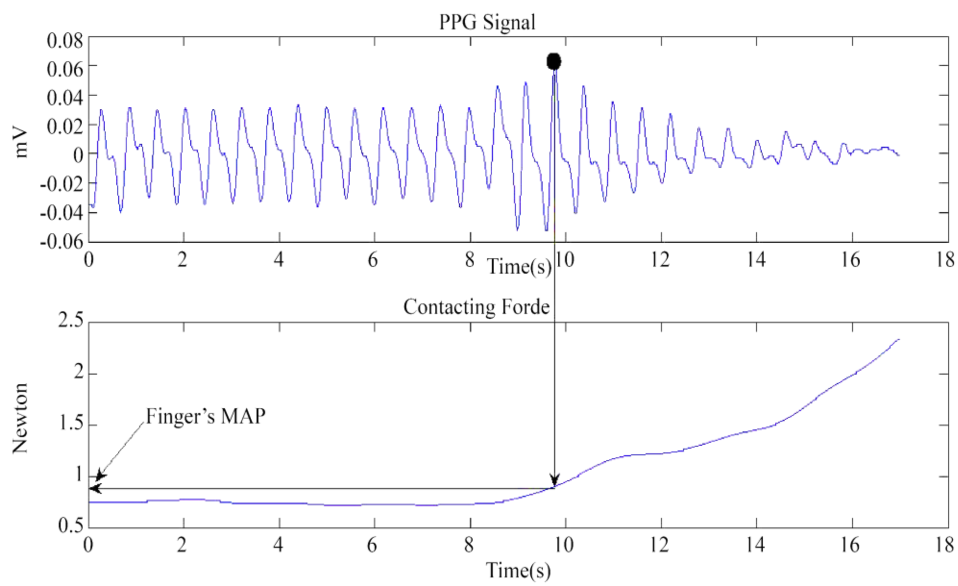

Fig. 3 The derivation of the finger MAP

Since the oscillation of oscillometric and pulsatile PPG signals is directly influenced by heart contraction, it can be hypothesized that correlations may exist between brachial MAP and finger MAP, as well as between finger MAP and blood pressure.

If such correlations are present, it could lead to further investigation into using PPG signals for estimating blood pressure, as the brachial MAP obtained from an oscillometric signal may empirically provide information about blood pressure.

3. Method

For this study, it is necessary to acquire simultaneous signals of photoplethysmography (PPG) and contacting pressure and simultaneous signals of Korotkoff sounds and cuff pressure. Since there is currently no commercially available device capable of recording finger contact force signals during PPG estimation simultaneously, a custom setup of the apparatus needs to be developed. Once the simultaneous signals are obtained, statistical comparisons can be performed between finger Mean Arterial Pressure (MAP), brachial MAP, and blood pressure. The specific details of each process are outlined below.

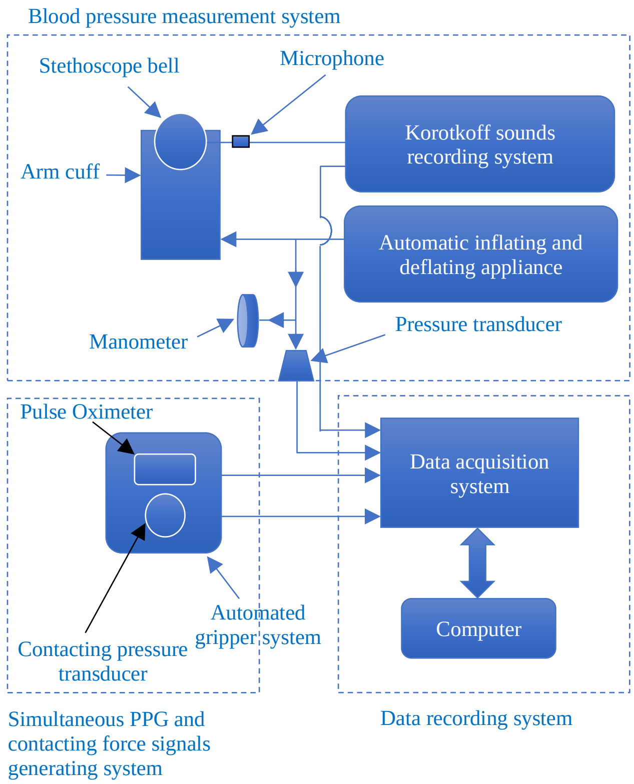

Fig. 4 The system set up to record simultaneous auscultatory and cuff pressure and simultaneous PPG and contacting force signals

3.1. Setup of the Signal Recording System

The system depicted in Figure 4 was utilized to record simultaneous signals of auscultatory and cuff pressure and simultaneous signals of photoplethysmography (PPG) and contact force. The system setup allowed for the acquisition of these signals simultaneously, enabling the study of their relationship and analysis.

The study's system consisted of three primary components: a blood pressure measurement system, a simultaneous photoplethysmography (PPG) and contacting force signal generating system, and a data recording system. Here are the details for each component:

i. Blood Pressure Measurement System:
- TeleMedCare Pty. Ltd.'s HCWS, a system for measuring blood pressure, was employed.
- A stethoscope (Part number: 927-0017, TeleMedCare Pty. Ltd.) was employed to capture the auscultatory waveform.
- The auscultatory waveform was transduced with the help of a built-in microphone (Hy-Q International, Part Number FM-10B).
- This microphone's frequency range of 20 to 16 kHz made it acceptable for reproducing Korotkoff sounds with excellent fidelity, which normally calls for a pass band between 20 and 300 Hz [25].

ii. Simultaneous PPG and Contacting Force Signal Generating System:
- The system allowed for the simultaneous generation of PPG and contacting force signals.
- Specific details about the components and mechanisms of this system are not provided in the given information.

iii. Data Recording System:
- A computer was utilized to display and store all signal recordings.
- The computer served as the central unit for data acquisition and storage during the study.

The blood pressure measurements in the study strictly followed a standardized procedure. The cuff pressure was incrementally raised, reaching approximately 180 mmHg at a rate of around 15 mmHg per second, thanks to the assistance of an electronically controlled mechanical pump. To release the pressure, a valve was employed, gradually reducing it at a rate of approximately 2-3 mmHg per second until it reached approximately 40 mmHg, at which point the recording process automatically terminated. Throughout the procedure, a pressure transducer that had been properly calibrated using a manometer was used to monitor the air pressure inside the cuff constantly. Notably, the manometer and pressure transducer were combined into a single device (Model: MLT1100/D, ADInstruments, Sydney, Australia). In summary, the system used in the study incorporated a blood pressure measurement system for auscultatory measurements, a simultaneous PPG and contacting force signal generating system, and a data recording system that employed a computer for display and storage of all recorded signals [26].

In the simultaneous generation of PPG and the contact force signal system, the following components and methods were used:

i. PPG Waveform Recording:
  - The index fingertip was used to obtain a PPG waveform.
  - A reflection mode infrared finger probe (Model: MLT1020FC, ADInstruments, Sydney, Australia) producing light at 940 nm was used to record the PPG signal.
  - The probe was positioned on the finger to measure the PPG signal accurately.

ii. Contacting Pressure Signal Recording:
  - The contact pressure of the finger was captured using a pressure sensor (Model: A201, Manufacturer: Flexi Force).
  - The pressure sensor had an operating range of 0–25 lb.
  - It was positioned to measure the external force applied to the measured finger.

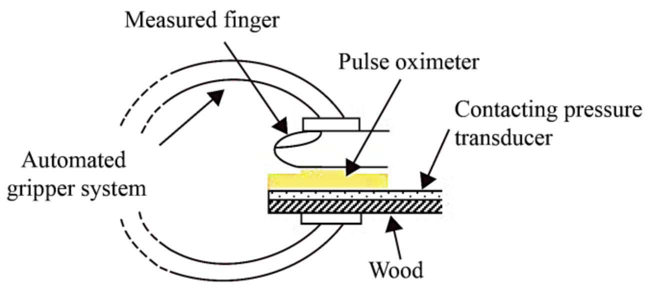

Fig. 5 An apparatus to generate simultaneous PPG and contacting force signals

iii. Finger Contacting Pressure Signal Generation:
- An automated gripper (Model: RG03A, MKII Gripper, China) was utilized.
- The gripper featured a servo motor linked to a programmable BBFuino board.
- The gripper methodically elevated the external pressure exerted on the measured finger throughout the recording of the PPG waveform.
- Precise control over the applied external pressure was maintained to ensure it exceeded the finger's Mean Arterial Pressure (MAP).
- The pressure level applied was substantial enough to effectively inhibit the arterial blood vessels in the finger, nearly occluding them.

The system enabled the simultaneous acquisition of both signals by combining the PPG waveform recording from the infrared finger probe and the measurement of the contacting pressure using the pressure sensor. The applied external pressure on the finger ensured that the finger MAP was exceeded, allowing for studying the relationship between the PPG signal and the contacting force.

Figure 5 depicts the apparatus that generates simultaneous PPG and contacting force signals.

In the data recording system, the following processes were employed:

i. Signal Digitization:
- All recorded signals, including the PPG waveform, contacting force signal, and auscultatory waveform, were digitized.
- To record the PPG and contact force signals, a data acquisition system (Model: ML880, ADInstruments, Sydney, Australia) was employed. This system allowed for precise sampling of the signals at a rate of 1 kHz, ensuring that the signal details were accurately captured for further analysis and interpretation.

ii. Computer Display and Storage:
- A computer was employed to display the recorded signals in real time.
- Additionally, the computer was used to store all signal recordings for further analysis and processing.

The data acquisition system facilitated the conversion of analog signals into digital format, allowing for precise and high-resolution recordings. The computer interface provided a convenient means to visualize the signals during the recording process, as well as efficient storage of the acquired data for subsequent analysis.

3.2. Raw Signal Acquisition

Simultaneous signals of photoplethysmography (PPG) and finger contacting pressure, as well as concurrent signals of Korotkoff sounds and cuff pressure, were gathered from a cohort of 30 healthy participants with an average age of 28 ± 5 years. To guarantee precise signal acquisition, participants received instructions to refrain from consuming caffeine for at least 12 hours leading up to the measurements. Throughout the collection of Korotkoff sounds and cuff pressure signals, participants assumed a comfortable seated position, with their hands resting on a pillow. The pillow was strategically positioned at heart level to ensure optimal measurement accuracy. Subsequently, a cuff was thoughtfully applied around the upper arm to facilitate the blood pressure measurement process. Following this procedure, the measurement of simultaneous PPG and finger contacting force signals was conducted. The pulse oximeter and the automated gripper system were placed on the same index finger as the arm used for the cuff pressure measurement. This ensured the pulse oximeter and gripper system were positioned on the ipsilateral (same side) finger.

3.3. Signal Pre-Processing

A downsampling procedure was implemented to process the recorded signals, which reduced the sampling rate from 1 kHz to 100 Hz. This downsampling served the dual purpose of decreasing computational demands and enabling more efficient signal analysis. Following data acquisition, both the cuff pressure signal and the PPG signal underwent distinct filtering processes. Specifically, the cuff pressure signal was subjected to a sixth-order bandpass Butterworth filter featuring a pass band that ranged from 0.5 Hz to 5 Hz. This specific filter configuration was selected based on the assumption of a maximum heart rate of 300 beats per minute (BPM). The purpose of this filtering process was to transform the original exponential decay profile of the cuff pressure signal into a pulsatile oscillometric waveform, which is more suitable for subsequent analysis. Similarly, the PPG signal was filtered using a first-order bandpass Butterworth filter with the same pass band of 0.5 Hz to 5 Hz. This filtering process aimed to refine the PPG signal by eliminating unwanted frequencies and preserving the relevant components for analysis. Using a bandpass filter allowed for the isolation of relevant frequency components associated with the pulsatile nature of the PPG waveform. Importantly, a forward-backward filtering approach was employed for both signals, ensuring a zero-phase response. This method avoids any phase distortion that could affect the timing and shape of the filtered signals, providing more accurate representations of the underlying physiological phenomena.

3.4. Non-Real Time Blood Pressure Estimation

In this research, a dedicated platform was constructed to mimic the blood pressure measurement procedure using recorded Korotkoff and cuff pressure signals. This platform faithfully reproduced the consecutive stages of conventional blood pressure measurement, thereby facilitating the systematic examination and evaluation of the recorded signals within a controlled and replicable environment. By reproducing the measurement process in this fashion, researchers could perform a thorough evaluation of the accuracy and efficiency of the proposed method for estimating blood pressure based on the recorded signals. A specially created MATLAB Graphical User Interface (GUI) software application, shown in Figure 6, was used to ease this assessment. This GUI tool played a vital role in facilitating the evaluation process. This GUI tool played a crucial role in the assessment process. This software visually presented the Korotkoff waveform to the observer, enhancing the clarity and ease of interpretation during the assessment. This graphical representation of the Korotkoff waveform aimed to enhance the observer's ability to identify and accurately estimate the occurrence of systolic and diastolic events and noise occurrences. Through the utilization of the GUI software tool, the human observer was afforded the capability to visually inspect and analyze the graphical depiction of the Korotkoff waveform. This visual representation enhanced the reliability of estimating systolic and diastolic events, aiming to elevate the consistency and precision of blood pressure estimation derived from the recorded Korotkoff and cuff pressure signals. This approach closely mirrored the standard measurement method employed in non-invasive blood pressure monitoring, ensuring alignment with established practices in the field.

During the blood pressure estimation process, annotations from two seasoned clinical experts, well-versed in conducting non-invasive blood pressure measurements, were employed. The auscultatory waveform and the cuff pressure were both shown graphically to these specialists at the same time. These experts were provided with two concurrent graphical representations of the signals: the cuff pressure and the auscultatory waveform. To enhance the precision of Korotkoff sound detection, the Korotkoff sounds underwent bandpass filtering within the range of 20 Hz to 300 Hz, a recognized range for achieving faithful reproduction of Korotkoff sounds. The cuff pressure signal, on the other hand, was left unfiltered. The auscultatory waveforms underwent forward-backwards filtering in order to get a zero-phase response. This filtering technique enhances waveform analysis's reliability by mitigating phase distortion.

The scorers were given parameters within the MATLAB GUI that allowed them to precisely adjust the time scale and amplitude scale of the filtered signal graphs. This flexibility facilitated improved signal visualization, thus assisting in accurately identifying systolic and diastolic events. The assessors also had the option of hearing the Korotkoff noises contained within the recorded auscultatory signal. They used headphones with a 20 Hz to 20 kHz frequency range, which effectively covered the pass-band of Korotkoff noises between 20 Hz and 300 Hz. This auditory capability enhanced their ability to make accurate assessments of the signals. This auditory capability enhanced their ability to assess and evaluate the signals accurately. The GUI provided a playback function with a time cursor, enabling the scorers to synchronize the audio recording with the plotted waveforms and make precise annotations based on their auditory perception. Overall, the combination of visual analysis of the signals and auditory assessment of the Korotkoff sounds, supported by the MATLAB GUI, allowed the scorers to accurately determine the systolic and diastolic events for blood pressure estimation.

In Figure 6, we can observe an illustrative instance of an annotated auscultatory waveform, which was achieved through the utilization of the radio button user interface control within the MATLAB GUI. This waveform depicts the recorded auscultatory signal, encompassing the Korotkoff sounds captured during the blood pressure measurement procedure. The graphical representation of the waveform serves as a visual aid, enabling the experts to perceive the signal's characteristics and create annotations for the systolic and diastolic events. The radio button user interface control, seamlessly integrated into the GUI, empowers the experts to designate and mark the systolic and diastolic events by simply clicking on the corresponding positions within the waveform using a computer mouse. This interactive functionality streamlines the annotation process, enhancing efficiency and contributing to the accurate identification of the target events.

Using the radio button control, the experts can clearly indicate the points in the waveform corresponding to the onset and cessation of the Korotkoff sounds, which indicate the systolic and diastolic pressures, respectively. These annotations serve as the basis for estimating blood pressure values. The example in Figure 6 demonstrates how the annotated auscultatory waveform visually represents the marked events, allowing for clear identification and reference during the blood pressure estimation process. After individually annotating the signals, the two experts worked together to resolve disagreements and reach a consensus on the estimated blood pressure. They reviewed their annotations, discussed any differences, and agreed upon a unified annotation. This final annotation, representing their combined expertise, was saved for later comparison and analysis.

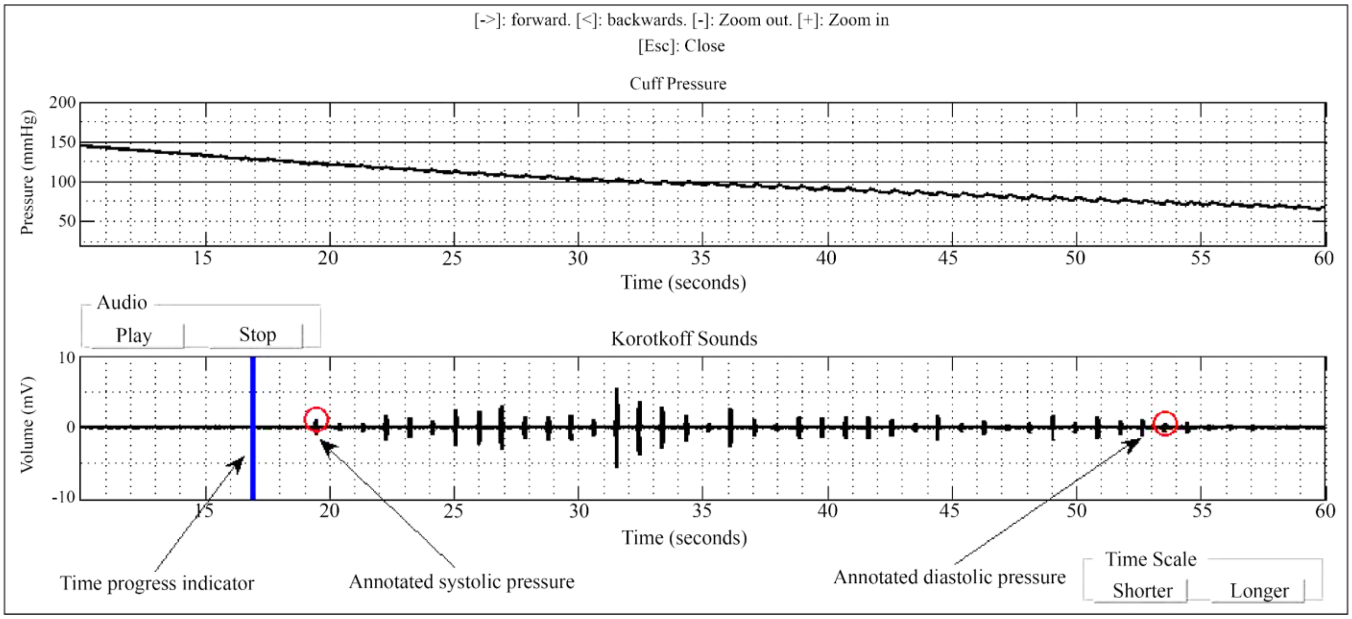

Fig. 6 A GUI for non-real-time blood pressure estimation

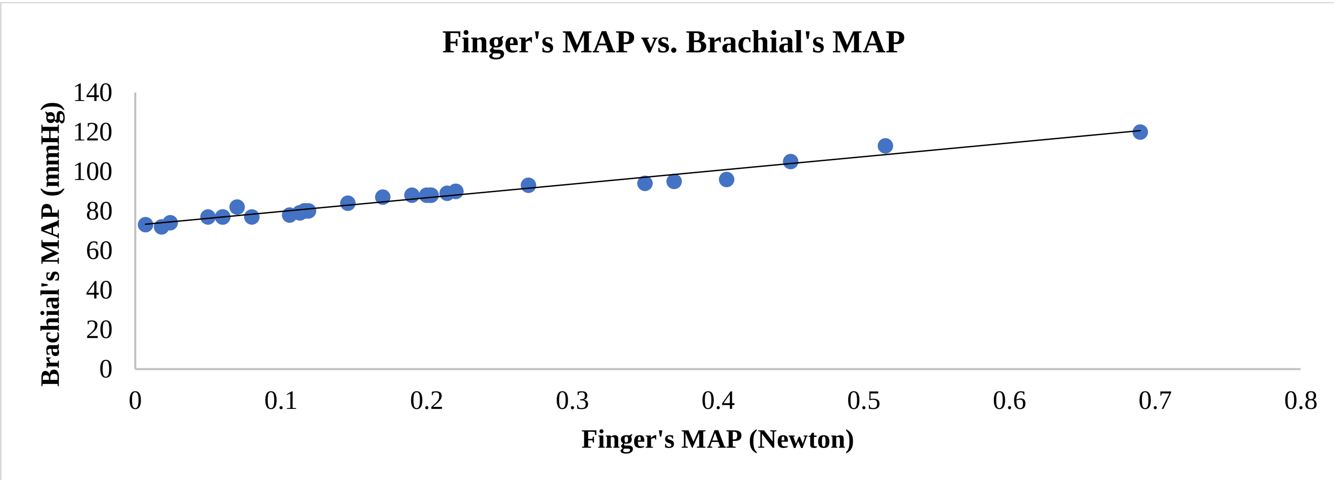

Fig. 7 Distribution of the Finger MAP derived versus the brachial MAP derived

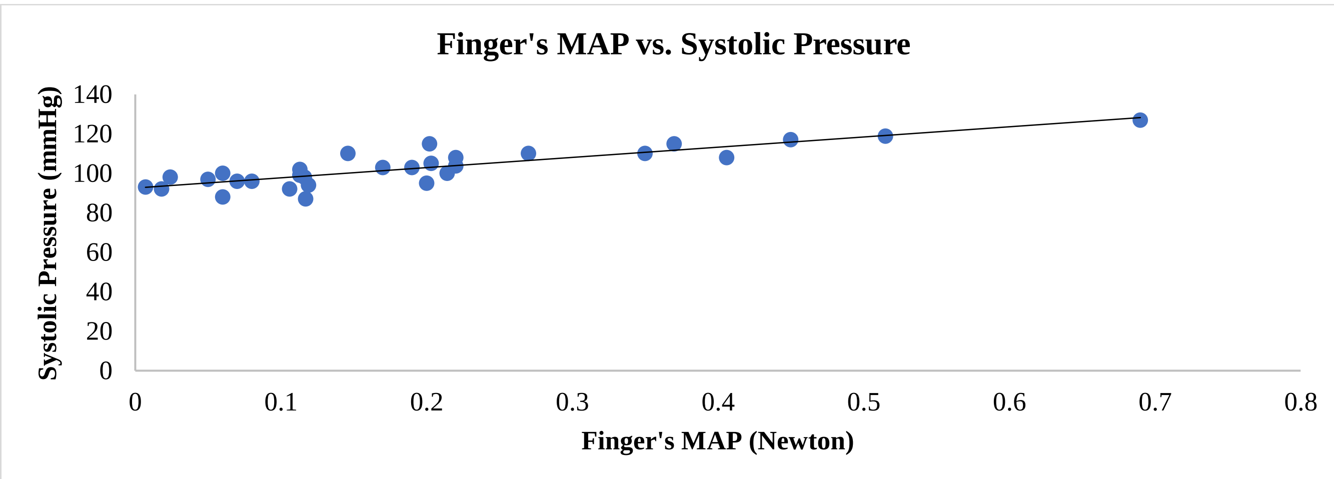

Fig. 8 Distribution of the derived finger MAP against the estimated systolic pressure

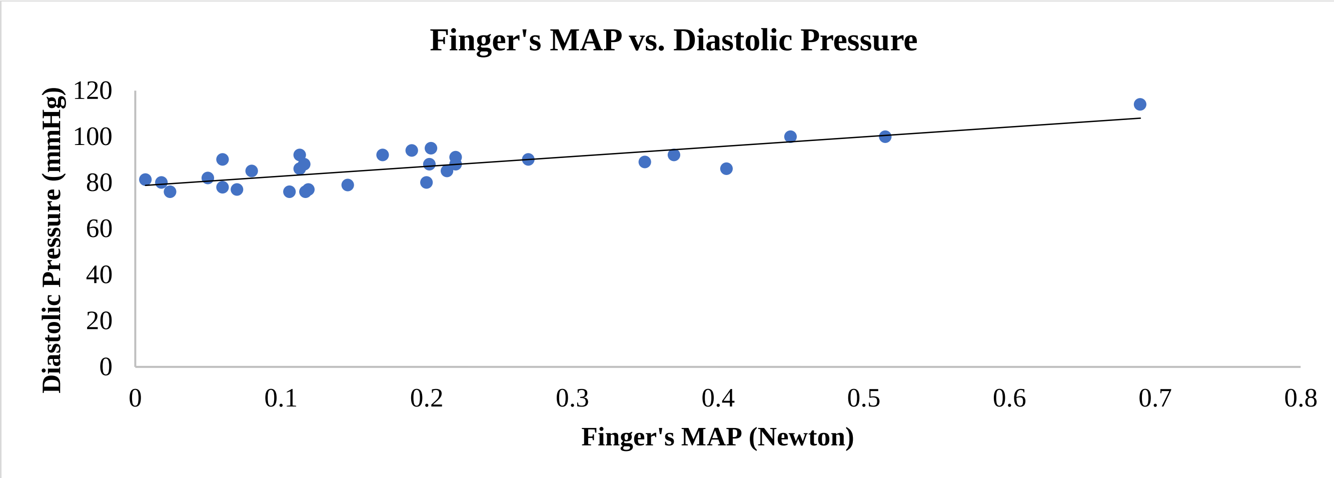

Fig. 9 Distribution of the derived finger MAP versus the estimated diastolic pressure

3.5. Statistical Analysis

The primary objective of the analysis utilizing the Pearson correlation coefficient was to determine the extent of the connection between finger MAP and brachial MAP. In statistical terms, the Pearson correlation coefficient serves as a valuable tool for quantifying the strength and direction of the linear relationship that exists between two variables.

In this particular context, one variable is represented by X, which stands for the finger Mean Arterial Pressure (MAP). In contrast, the other variable is represented by Y, denoting the brachial Mean Arterial Pressure (MAP). This coefficient quantifies how closely the variations in these two variables are related in a linear fashion. By calculating this coefficient, we can determine how closely the finger MAP and brachial MAP are correlated.

4. Results

4.1. Results of the Inter-Expert Agreement for Nonreal-Time Blood Pressure Measurement

Table 1 offers a comprehensive summary of the agreement between two human experts during the annotation process for systolic and diastolic events across the 30 auscultatory waveforms. This table offers insights into the extent of concurrence between the experts' annotations, thus providing a measure of the consensus and reliability in identifying these particular events within the waveforms. The table allows for a quantitative assessment of the agreement between the experts, providing valuable insights into the accuracy and consistency of their annotations.

4.2. Finger MAP Compared with Brachial MAP and Blood Pressure

Figures 7, 8, and 9 offer visual representations of the distribution of the calculated Brachial Mean Arterial Pressure (MAP), systolic pressure, and diastolic pressure, respectively, compared to the calculated Finger MAP. These figures provide graphical insights into the relationships among these variables.

Furthermore, Table 2 furnishes Pearson's correlation coefficient values, which signify the strength of the linear correlation between the Brachial MAP, systolic pressure, and diastolic pressure in relation to the Finger MAP. These coefficients quantify the degree of linear association between these data sets, providing a measure of their interdependence.

5. Discussion

5.1. Inter-Expert Agreement

The slight discrepancies noted in the estimates of systolic and diastolic pressure, as illustrated in Table 1, suggest a remarkable degree of consistency and reliability in the procedure for calculating blood pressure from the recorded Korotkoff waveforms by independent experts. These minor variations reinforce the confidence in the accuracy and precision of the blood pressure estimation process.

Table 1. Results of the inter-expert agreement (systolic and diastolic differences)

Approach	Mean ± standard deviation (mmHg)		
Possible Systolic Difference	-2.63	±	1.90
Possible Diastolic Difference	-3.12	±	2.51

Table 2. Pearson correlation coefficient, *r* for the derived brachial MAP, systolic and diastolic pressures, compared to the derived finger MAP

Approach	Pearson Correlation Coefficient, *r*	*P*-value
Finger MAP vs brachial MAP	0.9820	0.05
Finger MAP vs systolic pressure	0.8591	0.05
Finger MAP vs diastolic pressure	0.7915	0.05

5.2. Significance of the GUI Developed for Non-Real-Time Blood Pressure Measurement

A multitude of studies have put forth various systems for measuring blood pressure, integrating both visual and aural interpretation of recorded auscultatory waveforms [27, 28, 29]. These systems aim to address the limitation of observer errors inherent in the traditional auscultatory method by utilizing both hearing and visual analysis of signals. Wang et al. conducted a study demonstrating that a hybrid system, which combines both visual and aural interpretation of recorded auscultatory waveforms, provides blood pressure estimates comparable to those obtained through the conventional approach. These findings serve to validate the choice of the annotation method utilized in this study for blood pressure estimation.

Furthermore, since the nonreal-time blood pressure measurements were derived from the consensus of two experts who reconciled any scoring discrepancies, the resulting reference values are deemed highly reliable. The substantial agreement observed between the two scorers, as depicted in Table 1, underscores the confidence and assurance regarding the accuracy and dependability of the final reference values. This consensus among scorers signifies a strong concurrence in their annotations of systolic and diastolic events within the auscultatory waveforms. Such a high level of agreement bolsters the credibility and validity of the derived reference values, offering a robust foundation for subsequent data analysis and interpretation.

5.3. Correlation between Finger MAP and Brachial MAP and Blood Pressure, Respectively

Table 2 demonstrates strong correlations among the three pairs, as Pearson's correlation coefficients indicate. The corresponding graphs depicted in Figures 7, 8, and 9 further illustrate the close relationships between these parameters. However, it is worth noting that the correlation coefficient for finger MAP vs. diastolic pressure is the lowest. This discrepancy may be attributed to the challenges associated with accurately identifying the precise diastolic pressure in the given samples. The classification of Korotkoff sounds into five phases [30] provides valuable insights into the estimation of systolic and diastolic pressures:

- Phase I: This initial phase is characterized by the appearance of distinct tapping sounds corresponding to the palpable pulse.
- Phase II: As the measurement progresses, the sounds diminish in intensity and duration, becoming softer and more prolonged.
- Phase III: In this stage, the sounds become crisper and louder, signifying an intermediate point in the blood pressure measurement.
- Phase IV: The sounds transition to a muffled and softer quality during this phase, indicating the nearing completion of the blood pressure measurement.
- Phase V: The final phase occurs when the sounds completely disappear, signifying the diastolic pressure and marking the conclusion of the blood pressure measurement.

The presence of Korotkoff sounds during Phase I and their subsequent disappearance in Phase V are crucial indicators for estimating systolic and diastolic blood pressures, respectively. However, it is important to note that phase V may not always be clearly discernible in every case, as certain individuals may persistently exhibit sounds until the cuff is completely deflated. This phenomenon is more frequently observed in individuals with arteriovenous fistulas and aortic insufficiency [31].

If such cases are present within the recorded samples, it can pose challenges for experts in accurately deriving diastolic pressures. Moreover, based on the findings presented in Table 1, the difference in estimating diastolic pressure is more pronounced compared to systolic pressure estimation between the experts. This observation may suggest varying difficulty levels in accurately estimating both systolic and diastolic pressures.

5.4. The Study to Estimate Blood Pressure based on the PPG Signal

The utilization of the PPG signal for blood pressure estimation offers an alternative to the conventional arm cuff-based measurement method. This approach has gained significance due to the inconvenience and discomfort associated with cuff-based measurements. Consequently, there has been a rising interest in developing blood pressure measurement methods that do not require a traditional cuff (i.e. cuff-less). Numerous studies in recent years have focused on estimating blood pressure using the PPG signal [32]. The findings from these studies are noteworthy, demonstrating the potential of PPG-based techniques as promising alternatives for cuff-less blood pressure measurement. However, it is worth noting that none of these studies have incorporated the use of finger Mean Arterial Pressure (MAP) in their methods.

Additionally, to the best of our knowledge, there has been no investigation into the relationship between finger MAP and blood pressure estimation. Therefore, this study aims to fill this research gap by exploring the association between finger MAP and blood pressure estimation. By incorporating finger MAP into the analysis, we seek to enhance the accuracy and reliability of cuff-less blood pressure measurement techniques based on PPG signals.

5.5. Limitations of the Study and Future Work

The study conducted in this research involved healthy adult participants, and the measurements were performed within a controlled laboratory setting. It is important to note that the recorded blood pressure and PPG signals obtained from this specific sample may not represent all population categories. Blood pressure can vary among individuals based on their health status, age, and other factors. In future work, it is essential to consider a more diverse range of participants that encompasses various health conditions and age groups.

By including a broader spectrum of individuals, the study's findings can be generalized to a wider population and provide more comprehensive insights into the relationship between finger MAP and blood pressure estimation. By incorporating a more diverse participant pool, future studies can improve the applicability and validity of the findings, taking into account the potential variations in blood pressure measurements across different demographic groups. This will contribute to a better understanding the performance and limitations of cuff-less blood pressure measurement techniques using PPG signals in real-world scenarios.

6. Conclusion

In this study, a statistical approach was employed to investigate the correlation between Finger MAP and the components of blood pressure, namely SBP, DBP, and Brachial MAP. Finger MAP was derived from the PPG signal by gradually increasing the contacting force applied during signal generation. As the force increased, the amplitude of the AC component of PPG initially increased and then decreased until it reached a plateau. The Finger MAP was determined at the point where the AC component's amplitude was maximum. The study involved 30 healthy individuals from whom Finger MAP, SBP, DBP, and Brachial MAP were obtained. SBP and DBP were estimated using a non-real-time blood pressure measurement approach, where two experts independently annotated the Korotkoff sounds and reconciled any discrepancies in their scoring. The resulting agreement between the experts provided the SBP and DBP values.

Statistical analysis was conducted using the Pearson correlation coefficient to examine the relationship between Finger MAP and the blood pressure parameters. The results revealed a strong correlation between Finger MAP and blood pressure, indicating the potential for using the PPG signal to estimate blood pressure. These findings open up avenues for further research and exploration in the field of blood pressure estimation using the PPG signal. By leveraging the relationship between Finger MAP and blood pressure, innovative approaches and techniques can be developed for cuff-less blood pressure measurement, offering potential benefits such as convenience and improved user experience.

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