Wireless Wearable Photoplethysmography Sensors for Continuous Blood Pressure Monitoring

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Abstract— **Blood Pressure (BP) is a crucial vital sign taken into consideration for the general assessment of patient's condition: patients with hypertension or hypotension are advised to record their BP routinely. Particularly, hypertension is emphasized by stress, diabetic neuropathy and coronary heart diseases and could lead to stroke. Therefore, routine and long-term monitoring can enable early detection of symptoms and prevent life-threatening events. The gold standard method for measuring BP is the use of a stethoscope and sphygmomanometer to detect systolic and diastolic pressures. However, only discrete measurements are taken. To enable pervasive and continuous monitoring of BP, recent methods have been proposed: pulse arrival time (PAT) or PAT difference (PATD) between different body parts are based on the combination of electrocardiogram (ECG) and photoplethysmography (PPG) sensors. Nevertheless, this technique could be quite obtrusive as in addition to at least two contacts/electrodes to measure the differential voltage across the left arm/leg/chest and the right arm/leg/chest, ECG measurements are easily corrupted by motion artefacts. Although such devices are small, wearable and relatively convenient to use, most devices are not designed for continuous BP measurements. This paper introduces a novel PPG-based pervasive sensing platform for continuous measurements of BP. Based on the principle of using PAT to estimate BP, two PPG sensors are used to measure the PATD between the earlobe and the wrist to measure BP. The device is compared with a gold standard PPG sensor and validation of the concept is conducted with a preliminary study involving 9 healthy subjects. Results show that the mean BP and PATD are correlated with a 0.3 factor. This preliminary study shows the feasibility of continuous monitoring of BP using a pair of PPG placed on the ear lobe and wrist with PATD measurements is possible.**

I. INTRODUCTION

Despite the fact that hypertension is one of the most important preventable contributors to diseases, it has no symptoms. Many people are unaware of their hypertension condition until an adverse event occurs. Long-term abnormal blood pressure (BP), such as hypertension, can lead to heart disease, stroke, and damage to major organs. It was estimated that over 14 millions of patients in the US (39.4%) were not aware of their hypertension, while 66.9 million (53.5%) estimated patients did not have their condition controlled [1]. The World Health Organization reported in 2016 that one-third of worldwide adults have high BP. To assess this condition and prevent complications, patients with hypertension have to be monitored routinely by healthcare providers. BP measurement is usually performed during routine health examinations, but the collected data can be affected by environmental factors or patient's mood, nervousness or emotion - also referred as "white coat" effect, which can lead to an elevated BP. To better monitor the condition, patients are generally advised to record their BP themselves on a daily basis to provide more accurate data for their healthcare providers to decide on appropriate therapeutic intervention. Taddei et al. demonstrated that a large population of patients cannot maintain their BP in the normal range; anti-hypertension drugs are proven to be effective, but are often not administrated at the correct dosage [2]. It is suggested that pharmacological treatments for hypertension should consider the degree of BP reduction, and the effective duration of the drug. As patient's condition may deteriorate over age, treatments have to be reviewed regularly, and long term BP measurement is essential to enable accurate treatment design.

There are two major types of non-invasive BP measurement methods. One method widely applied clinically is the use of a sphygmomanometer and stethoscope. The point of systolic and diastolic BP can be detected by auscultation, capturing the sound of pulses when blood flows through the upper arm arteries under pressure, or oscillometry, using the empirical method to detect the oscillation [3]. However, this approach is prone to motion artefacts [4], and cannot be used for 24-hour monitoring. Non-invasive long term and continuous BP measurement methods have been proposed and are mostly based on pulse arrival time (PAT). With wearable devices placed at strategic body parts, this technique is more comfortable compared to volume-clamp and tonometry-based methods [4], [5]. A combination of electrocardiogram (ECG) and photoplethysmogram (PPG) sensors are usually used to measure PAT and estimate BP. As ECG sensors are designed to capture electrical signals of the cardiac cycle with no latency, this signal is used as the reference for measuring PAT. PPG sensor can measure the light intensity variation of the oxygenated (HbO_2) haemoglobin in the blood. The measured pulses are the result of the fluctuation of blood volume during systolic and diastolic heart phases [6]. PPG sensors have been used to detect pulses on different body parts such as fingertip, wrist, brachial, forehead, chest, earlobe, and ankle [6].

Different approaches have been suggested for measuring PAT by capturing the latency of PPG signals on different positions of the body using the ECG signal as reference. Difference of PAT (PATD) have also been stated to measure PAT difference between the toe and finger, or the brachial and ankle [7], [8]. Y. Zheng et al. [9], [10] have developed a wearable cuff-less system for BP monitoring, using an armband for measuring ECG and PPG signals. H. Lin et al. [5] similarly introduced

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a system consisting of a chest strap for ECG measurement and a wristband for PPG sensing. This wearable system can transmit data to a PC or mobile device via Bluetooth and enable continuous monitoring of BP. P. Sawa et al. [11] have developed a 4cm length sensor patch which integrates ECG and PPG sensors. By attaching the patch to the sternum, it can capture the pulse wave transit time (PWTT) and estimate the BP. Nitzan, M et al. [7] studied the relationship of PATD between the toe and finger and the systolic BP (SBP). Chen et al. [12] elaborated a multi-sensor system for measuring the PATD between the finger and ankle to detect diabetic peripheral neuropathy, using the ECG sensor as the reference. However, these methods have limitations: long term use of electrodes/patches brings about discomfort and ECG signal can be corrupted with motion artefacts. In addition, it requires stable contacts with at least two nodes placed as far as possible from each other on the body to acquire the voltage difference exerted during cardiac cycle: synchronization between the wearable ECG and PPG sensor is challenging for accurate measurement. This paper shows a novel approach for pervasive measurement of PATD and estimation of BP. Instead of relying on ECG signals, two PPG sensors placed on the wrist and on the earlobe are used to deduce PATD and estimate BP. In addition to continuous BP monitoring, the sensors are placed at locations that do not disturb the user or break one's work flow of daily activities: ear clips and wristbands are common choices for accessories, jewellery and wearable devices. The development of this approach is not only to enable continuous BP measurements, but it also considers the ergonomics and user compliances for long term measurements [13].

II. METHOD

M.W Wukitsch et al. [14] describes the physical interaction and particular absorption of red light by HbO_2. Blood flow and pulse can be detected and monitored by measuring the outcome intensity signal of red light after interaction with blood vessels: this is the main principle of pulse oximetry.
As more extensively described in previous work [15], the device used is based on optic technique and particularly includes as depicted in figure 1 a photodetector and a red LED (660nm). This compact device (11x18mm) is wireless and connects to a mobile application via Bluetooth Low Energy (BLE); multiple sensors can be connected to a smartphone at once. Real time data visualisation and transfer to a cloud server allows the clinical team, patients and carers to simultaneously access the data. An on-node sensor interface program is developed and which is similar to [15] without use of infrared (IR) LED and no noise measurement. As the red LED is always switched on, the photodetector measures the intensity of light reflected from the skin. A calibration implementation allows both the intensity of the LED (PWMRED) and the gain of the amplification of the outcome signal (G) to adapt according to the strength of the outcome signal. It was showed that the device can reliably detect pulses [15]. By placing one sensor at the earlobe and another one at the wrist, it is aimed to show that BP can be measured through PATD calculation. This device will be referenced as the ICL (Imperial College London) sensor.

Following ethical approval granted by the NHS South East London Research Ethics Committee 3 in December 2010 (10/H0808/124), experiments on healthy subjects was conducted. 9 volunteers aged between 23 to 29 years old, of number 3 skin tone according to the Fitzpatrick scale [15], considered healthy with no alcoholic or smoking prior were recruited in this study. Table I shows physical details about each subject. To obtain different BP values and to verify the effect of various postures and activities on BP and PATD, every subject was tested at rest for the following postures: sitting, supine and standing. Participant 1 to 5 included had their BP and PATD monitored after physical exercises and listening to music with high rhythm on a sited posture. Specifically, one sensor was attached to the radial artery at the wrist using a wristband with elastic bands and the other one was attached to the earlobe, using an ear clip. To compare the obtained results of the proposed device, another PPG sensor called Pulse Sensor developed by Joel Murphy and Yury Gitman was used. This sensor will be referenced as PS (pulse sensor). Integrated with the Imperial Body Sensor Network (BSN) platform for data collection at 500Hz sampling rate, the sensor is designed with a green LED light source which is mainly absorbed by HbO_2. Two Pulse Sensors were used and placed at the other body side of the subject on the ear lobe and the wrist. Figure 2 shows the experimental set up with all material involved. All experiments were taking place after at least 30 minutes following any food ingestion. For each activity or position, BP measurement was taken before and after and the final BP used is the average of those two measurements. Before the experiment, subjects were asked to remain quiet and relaxed for a couple of minutes. Pulse measurement was then collected for 1 minute, except for the exercising activity for which the duration was shorten to 30 seconds to prevent quick recovery that might affect validation. In the sited position, participants were asked to rest their arm on the desk, almost horizontal at mid-sternum with palms upwards (see figure 2). In the standing posture, one's arms were naturally placed along one's side. In the supine posture, one's arms were placed on the bed with palms upwards as well. For the exercising task, female participants were asked to perform 20 squats whilst male were instructed to perform 20 push-ups or sit-ups. Data were collected about 3 minutes after each body posture or change to allow BP does to stabilize - except for exercising for which BP measurement was done immediately afterwards. All participants did the same experiment on two different days. During the entire experiment, volunteers were required to keep silence during blood pressure and pulses measurements.

III. RESULTS

To measure the PATD, an algorithm described in figure 3 was developed on Matlab. After smoothing of the two signals, a best fitted Gaussian function is then calculated for each signal. The mean and standard deviation of the Gaussian

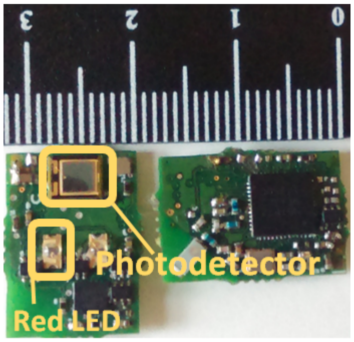

Fig. 1: Bottom and top views of the device.

TABLE I: Physical details about the volunteers

Subject	Height (cm)	Weight (kg)	Sex
1	162	58	F
2	172	60	F
3	165	45	F
4	158	51	F
5	185	98	M
6	176	85	M
7	172	62	F
8	182	97	M
9	159	47	F

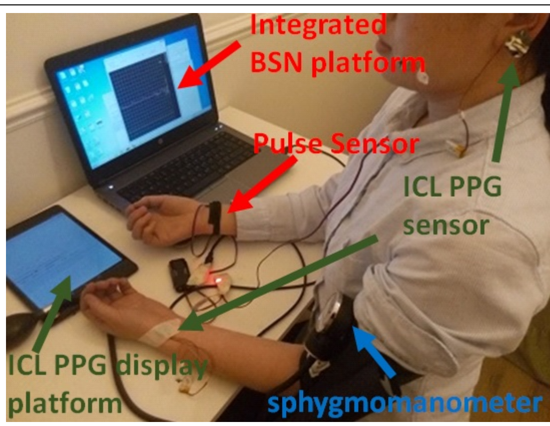

Fig. 2: Experiment set up. The sensors are placed at the wrist and ear. On one side, the ICL (Imperial College London) sensor is placed while on the other side, the Pulse Sensor is used. The Pulse Sensor is connected to the integrated BSN platform on the laptop. ICL sensor is the introduced device which is connected via mobile application to a tablet using BLE technology.

function is previously derived empirically. The maximum of the probability distribution (MPD) is then calculated as maximum of the multiplication of the pulse with the Gaussian's corresponding value. To increase true positive results in the peak detection, the points surrounding the MPD were evaluated to detect the highest value. Once all pulses are discovered, the sum of all peak difference between the signals is calculated and divided by the minimum number of peaks for all signals. Figure 4 shows the Gaussian functions in dot line, results of MPD is in dash line, the signal is in solid line. The MPD is marked in a red dot, the point before is marked in cyan and the point after is marked in green. The final decision about the point considered as a peak is circled in black.

To validate the algorithm's efficiency, results were compared with hand selection of peaks (considered as the gold standard). Classification results show that the algorithm is able to determine 61% of true positive matches (38% of false positive matches) with 23% of additional detected peak compared to the actual number of peaks. On figure 4, the highlighted area on the pulse signal shows the limitation in the ability of the algorithm in adapting to the average width of the pulses and the average frequency of the apparition of peaks. The final decision on the MPD on this highlighted area is erroneous because the means of Gaussian functions are not sufficiently aligned with the pulse signal. Further research using adaptive standard deviation and mean of the Gaussian function could possibly reduce the occurrence of false positive outcome and therefore enhance the accuracy of PAT measurement. The adaptivity should also take into consideration possible heart rate changes and signal distortion.

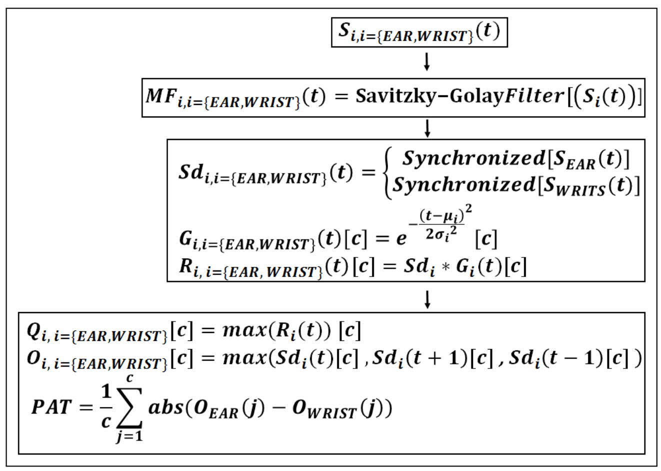

Fig. 3: Signal processing program. SI,I={EAR,WRIST}=signal from I; MFI,I={EAR,WRIST}=Smoothed signal I; SdI,I={EAR,WRIST}=synchronized signal I according to absolute time; c= number of Gaussian or maximums or peaks; GI,I={EAR,WRIST}=Gaussian distribution with mean= μ_I and width=σ_I^2; RI,I={EAR,WRIST}=probability distribution of the signal I to be a peak; QI,I={EAR,WRIST}=maximum of each probability distribution I; OI,I={EAR,WRIST}= final maximum value decision based on values surrounding the highest Gaussian of peak probability; PAT=final PAT measurement.

Figure 5 shows an example of PPG data taken from participant 1 using the ICL sensor. From the data, running the previously explained algorithm, the PATD is calculated. Figure 6 shows the functions determined with the different BP (systolic BP (SBP), mean BP (MBP) and diastolic BP (DBP)) and PATD measured over all the postures and

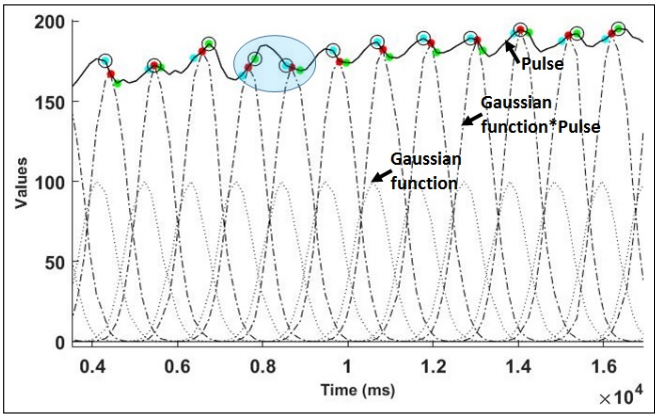

Fig. 4: Example of peak detection using the algorithm describe in fig.3

activities for subject 1 - figure 6a provides those functions with the ICL sensor while figure 6b shows those using PS. The corresponding slopes of the different functions for each BP types are similar over the two sensors. Those functions depend on the subject's preliminary results from which they are calculated. Possible BP measurement could be performed on real time basis, prior enough preliminary data of BP and PATD have been gathered for the elaboration of personalised functions linking BP with PATD. A paired t-test with p-value under 5% was performed. Results show that no significant difference is found between the two sensors for all subjects with a p-value of 0.257. Among the calculated slope for all subjects using the ICL sensor, no significant difference is found with a p-value of 0.536; using the PS, the p-value is 0.984. Consequently, generalised functions linking PATD and BP can be found for particular pathologies and patient's general condition. The linear relation between PATD and BP suggests that a correlation factor can be measured.

The Moens-Korteweg equation [16], which states that the pulse wave velocity (PWV) is negatively correlated to the vessel elasticity, also indicates a negative correlation between the BP and the PATD as the elasticity is exponentially linked to BP. Tables II and III show the correlations values of the different BP (SBP, MBP and DBP) and PATD (PAT, PAT^2 and $ln(PAT)$) for each subject respectively using the ICL sensor and PS. For both devices, subjects 6 does not follow the enunciated rule - similarly, participants 2 and 5 have positive correlation using the ICL sensor. The average of the different correlation results over all subjects are similar for the different calculation methods within each device's dataset. The highest averaged absolute correlation value is found for DBP/$ln(PAT)$ at 0.305 for the ICL sensor and 0.365 for the PS (highlighted in blue on the tables II and III). This result is coherent with the Moens-Korteweg equation which exponentially links the BP and the elasticity from which the PATD is dependent - as change in blood vessel's volume allow PPG measurement. Increasing the number of volunteers could better validate the correlation factor reliability (as subjects 5 and 6 provided abnormal results compared to the others and expected). Particularly, among the subjects, for each sensor, different t-tests were applied with a p-value under 5%:

- within the same correlation function,
- between the same BP category and different PATD function,
- between SBP and DBP categories for the same PATD function,

Results show that for the ICL device, there is no significant difference found. The PS provides significantly different datasets within the same correlation function for the MBP-PAT, SBP-PAT^2 and the MBP-$ln(PAT^2)$ (highlighted in red on table III). Within the PS, no other significant difference was found for the other datasets. Generally, there is homogeneity in the results gathered from each sensor among the participants and BP categories. A final paired t-test at the p-value under 5% of the same type of BP and PATD over the two sensors showed that all correlations were not significantly different with a respective p-value of 0.986, 0.448, 0.524, 0.747, 0.472, 0.583, 0.875, 0.429 and 0.501 for SBP-PAT, DBP-PAT, MBP-PAT, SBP-PAT^2, DBP-PAT^2, MBP-PAT^2, SBP-$ln(PAT^2)$, DBP-$ln(PAT^2)$ and MBP-$ln(PAT^2)$. These outcomes imply that both devices are providing equivalent results for the PATD measurements.

All those results finally suggest that the mutual evolution of PATD and BP should follow the Moens-Korteweg equation and therefore validate the initial hypothesis - continuously monitoring BP using PATD measurement. Figure 7 shows the different BP (SBP, DBP and MBP) measurements taken for the different postures and activities (see figure 7a) and subjects (see figure 7c). Over the different postures, as expected, the SBP is higher than the MBP which itself is higher than the DBP. Each BP category shows similar medians. Sitting and standing postures have wider BP ranges, with the highest recorded BP for the physical exercise and standing postures. Listening to high rhythm music and sat down after exercise activities have the most compact BP ranges. Supine posture shows the lowest recorded BP. Among the different subjects, figure 7c shows that a similar order is found between the different BP categories. Although participants 1 to 5, 7 and 9 show relatively low variation in BP among postures and activities, the others are wider. Subjects 5, 6 and 8 have high SBP values. Figure 8 shows the PATD over the different postures and activities (see figure 8a) and subjects (see figure 8b) for both sensors. For both figures, the PATD values from the ICL sensors are higher than the one from the PS with similar variation among subjects and postures and activities. Particularly, despite high SBP values recorded for subjects 5, 6 and 8, their PATD values measured from both devices are similar to the other participants. This might suggest a different blood vessel elasticity according to the Moens-Korteweg equation. The blood vessel elasticity parameter have been introduced as a limitation for the use of PWV (and consequently PATD) measurement for BP monitoring as it evolves with age while being inherent to the subject's pathology and quality of life [17]. Therefore, prior to BP monitoring using PATD, either a strong blood vessel elasticity measurement or a trained system providing calibration between BP and PATD is required. Results in figures 8a and 7a correlate with previous findings as for example, sitting at rest after physical exercise activity provide the lowest PATD median and the highest BP median for both devices. Similarly, the supine position shows the highest PATD and the lowest BP for both devices. Those results allow classification of the different postures and activities according to the BP results, from the highest to the lowest: physical exercise, standing, sitting, listening to music of high rhythm and supine postures. Likewise, PATD classification from the lowest to the highest provides the same ranking. Those results are coherent with previous work led by Caird & all [18] and Terént & all [19].

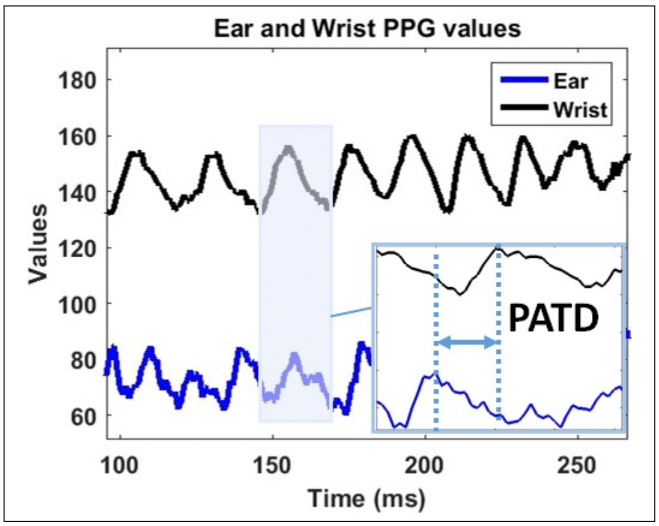

Fig. 5: Example of ear an wrist PPG taken from subject 1

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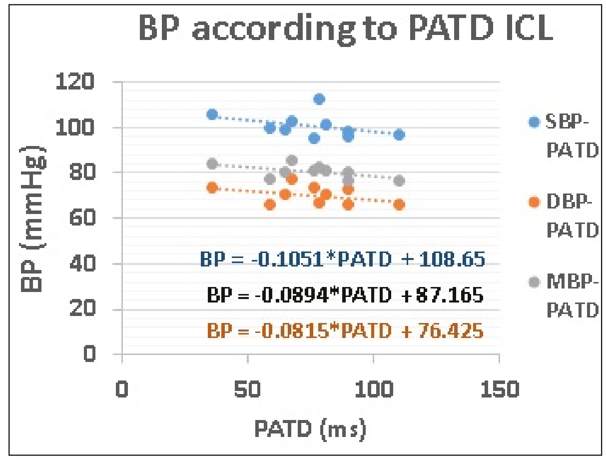
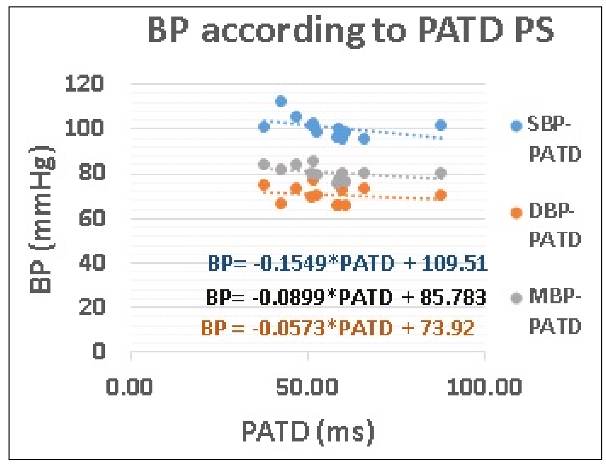


(a) $BP = f(PATD)$ over all postures of subject 1 using the ICL sensor.



(b) $BP = f(PATD)$ over all postures of subject 1 using PS.

Fig. 6: Different BP according to PATD for all activities/postures of subject 1.

IV. DISCUSSION

Daily BP measurements is crucial for managing chronic illness especially for patients with hypertension. Conventional BP measurement tools can only provide limited information regarding the patient's condition as only discrete measurements can be taken. Being able to provide continuous BP measurement with minimum burden and patient's involvement could facilitate disease management and prevention through identifying factors which affects BP. A pervasive wearable sensing platform is introduced for which the sensors are placed at the ear lobe and the wrist for continuous measurement of PATD from which BP is deduced.

As previously introduced [15], the wireless, light weighted and compact ICL device can be placed anywhere on the body and detect pulses. An elaborated algorithm for peak detection based on Gaussian function is also proposed. Based on the maximum of the multiplication of the Gaussian function and the signal, more than 60% of true positive outcome is measured. Limitations come from the lack of adaptation of the width and standard deviation of the Gaussian function according to the width and peak frequency of the investigated signal. Future research include adaptive algorithm with its integration within the mobile application. Using another PPG device as a comparison of the results, experiments were conducted. 9 healthy volunteer subjects were asked to perform and follow different postures and activities that are known to affect both BP and PATD. For each subject, a linear relation was found between the BP and PATD. Although the slope of the curve was different among subjects and the devices, no significant difference was found. Therefore, possible personalised equation linking the BP and PATD can be established if prior calibration is carried out. Further research should also include classification of data following the pathology and subject's general health condition to eventually avoid any calibration. Indeed, direct calibration and adaptiveness to the patient would potentially increase the clinical and social impact of such use of wireless wearable sensor for continuous blood pressure monitoring. Those results show that in addition to suggesting that both devices are giving similar

TABLE II: Correlation values of the different BP and PATD for each subject among postures and activities using the ICL sensor

Subjects	SBP/PATD	DBP/PATD	MBP/PATD
1	-0.41	-0.412	-0.579
2	-0.354	-0.368	-0.206
3	-0.249	-0.750	-0.634
4	-0.245	-0.438	-0.451
5	-0.041	0.241	0.193
6	0.313	0.601	0.572
7	-0.275	-0.0778	-0.152
8	-0.540	-0.789	-0.788
9	-0.918	-0.823	-0.883
Average	-0.01	-0.278	-0.148
Subjects	$SBP/PATD^2$	$DBP/PATD^2$	$MBP/PATD^2$
1	-0.413	-0.433	-0.599
2	0.363	-0.347	-0.179
3	-0.193	-0.693	-0.574
4	-0.247	-0.373	-0.400
5	-0.014	0.279	0.237
6	0.253	0.553	0.5223
7	-0.354	-0.161	-0.235
8	-0.523	-0.791	-0.786
9	-0.896	-0.811	-0.868
Average	-0.01	-0.255	-0.141
Subjects	SBP/$ln(PATD)$	DBP/$ln(PATD)$	MBP/$ln(PATD)$
1	-0.398	-0.433	-0.547
2	0.342	-0.392	-0.236
3	-0.313	-0.803	-0.694
4	-0.243	-0.505	-0.503
5	-0.086	0.203	0.152
6	0.376	0.649	0.622
7	-0.189	0.009	-0.065
8	-0.558	-0.786	-0.789
9	-0.939	-0.833	-0.897
Average	-0.012	-0.305	-0.155

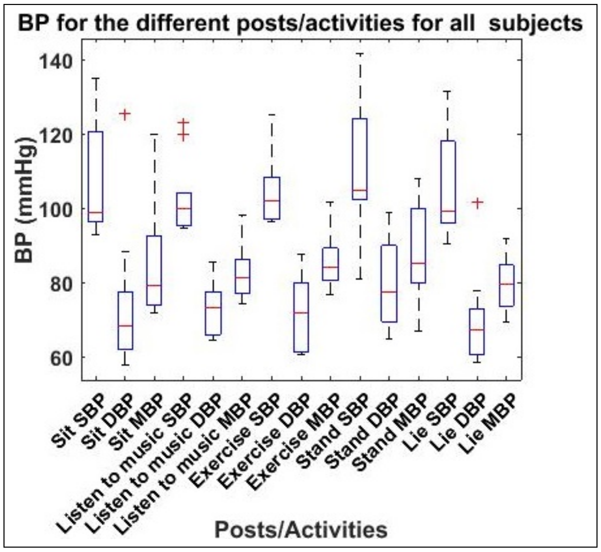
TABLE III: Correlation values of the different BP and PATD for each subject among postures and activities using PS

Subjects	SBP/PATD	DBP/PATD	MBP/PATD
1	-0.471	-0.024	-0.281
2	0.039	-0.377	-0.368
3	-0.111	-0.397	-0.328
4	0.022	-0.178	-0.138
5	-0.298	-0.494	-0.474
6	0.187	0.453	0.428
7	-0.344	-0.211	-0.262
8	-0.272	-0.489	-0.477
9	-0.776	-0.084	-0.247
Average	-0.189	-0.337	-0.3
Subjects	$SBP/PATD^2$	$DBP/PATD^2$	$MBP/PATD^2$
1	-0.365	-0.017	-0.216
2	-0.01	-0.413	-0.413
3	-0.166	-0.361	-0.319
4	-0.04	-0.245	-0.222
5	-0.346	-0.458	-0.454
6	0.217	0.452	0.431
7	-0.378	-0.239	-0.294
8	-0.339	-0.317	-0.343
9	-0.359	-0.468	-0.477
Average	-0.179	-0.288	-0.258
Subjects	SBP/$ln(PATD)$	DBP/$ln(PATD)$	MBP/$ln(PATD)$
1	-0.577	-0.028	-0.344
2	0.065	-0.334	-0.311
3	-0.089	-0.449	-0.361
4	0.08	-0.108	-0.056
5	-0.252	-0.527	-0.492
6	0.161	0.456	0.4277
7	-0.307	-0.179	-0.229
8	-0.116	-0.08	-0.093
9	-0.181	-0.537	-0.499
Average	-0.192	-0.365	-0.329

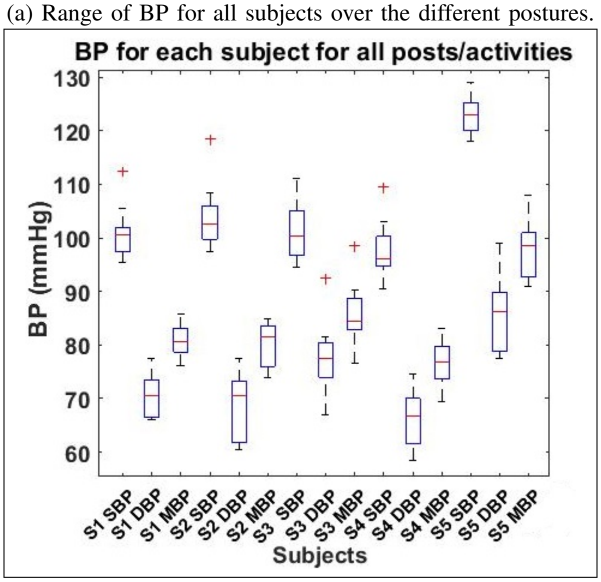
PATD measurement, a correlation factor can be measured. Maximum correlation factor was found for the DBP/$ln(PAT)$ at about 0.3 for both devices. This additionally shows that the introduced device gives highly similar results to the other standard PPG devices. Furthermore, the logarithmic function involvement affirms the Moens-Korteweg equation for which the blood vessel's elasticity - from which PATD is dependent, as it measured blood volume which changes following blood vessel's malleability - is exponentially dependent of the BP. Although the coefficient factor is low, increasing the number of participants in the study could improve its reliability (particularly, subjects 6 and 5 produced poor results compared to the others). Further significance analysis indicates that there is a general homogeneity among the participants and the BP categories within each sensor and between sensors. Similarly, those results indicates that both sensors give similar results. Following the Moens-Korteweg equation, mutual PATD and BP evolution should be observed. Detailed analysis of the different BP categories and PATD among participants, postures and activities and devices points to the negative correlation of the two parameters. Classification of the different postures and activities according to the BP results can be performed: physical exercise gives the highest BP value, while standing, sitting and listening to music of high rhythm have lower BP, and finally the supine posture has the lowest BP value. On the contrary, the PATD values are low to high for the same postures and activities list. Finally, this result also show similar measurement between the devices. Consequently, the presented device is able to capture signal and thus provide similar PATD measurements. This paper demonstrated the possible use of a seamless wearable wireless PPG sensors system for the continuous monitoring of BP using PATD measurements.

V. CONCLUSIONS

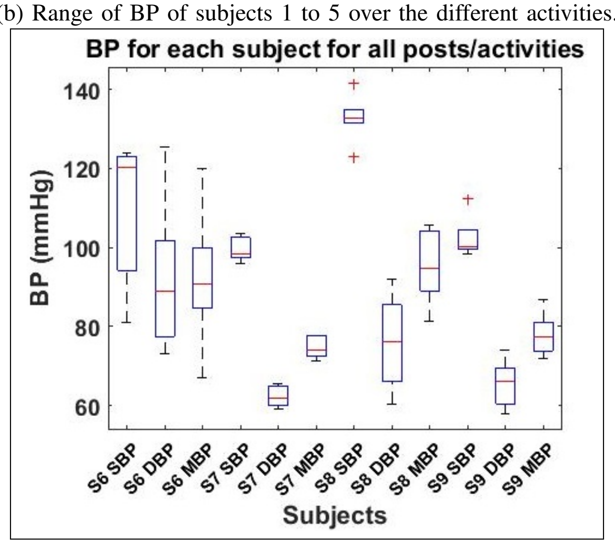
A new wireless wearable device was introduced: light weighted, small, pervasive and with ubiquitous access to data, its ability to provide continuous assessment of blood pressure without disturbing the user and one's daily activities through PATD has been demonstrated. Further research includes a more extended experimental study involving more participants of different age ranges, sex, skin tones following the Fitzpatrick scale, physical conditions (healthy or chronically ill), daily activities and activities affecting both PATD and BP, and such, at different time of the day in order to provide a more reliable BP measurement from PATD.



(a) Range of BP for all subjects over the different postures.

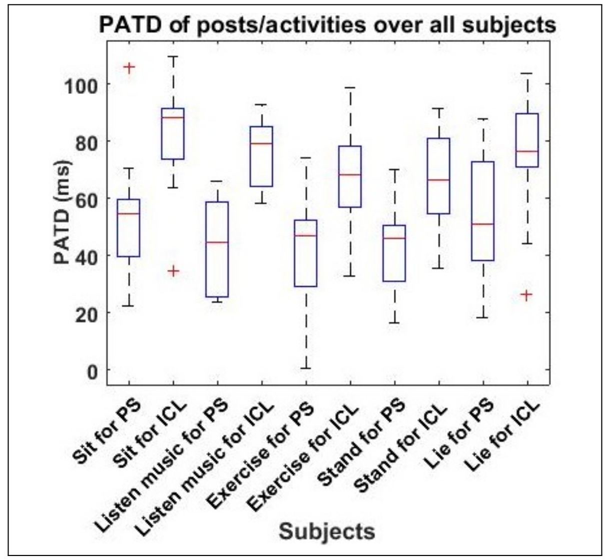


(b) Range of BP of subjects 1 to 5 over the different activities.

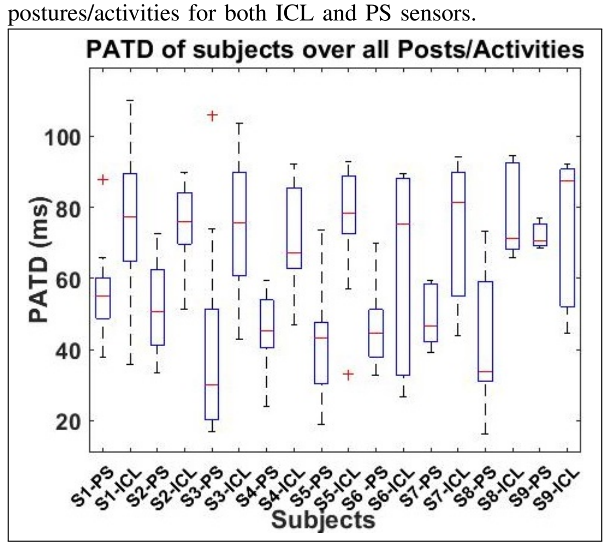


(c) Range of BP of subjects 6 to 9 over the different activities.

Fig. 7: Different ranges of BP results.



(a) Range of PATD for all subjects over the different postures/activities for both ICL and PS sensors.



(b) Range of PATD of each subjects over the different activities for both ICL and PS sensors.

Fig. 8: Different ranges of PATD results

REFERENCES

[1] C. for Disease Control, P. (CDC, *et al.*, "Vital signs: awareness and treatment of uncontrolled hypertension among adults–united states, 2003-2010.," *MMWR. Morbidity and mortality weekly report*, vol. 61, p. 703, 2012.

[2] S. Taddei, R. M. Bruno, and L. Ghiadoni, "The correct administration of antihypertensive drugs according to the principles of clinical pharmacology," *American Journal of Cardiovascular Drugs*, vol. 11, no. 1, pp. 13–20, 2011.

[3] M. Ward and J. A. Langton, "Blood pressure measurement," *Continuing Education in Anaesthesia, Critical Care & Pain*, vol. 7, no. 4, pp. 122–126, 2007.

[4] P. M. P. da Silva, *A pervasive system for real-time blood pressure monitoring*. PhD thesis, masters thesis, Dept. of Eng., Univ. of Porto, 2013.

[5] H. Lin, W. Xu, N. Guan, D. Ji, Y. Wei, and W. Yi, "Noninvasive and continuous blood pressure monitoring using wearable body sensor networks," *Intelligent Systems, IEEE*, vol. 30, no. 6, pp. 38–48, 2015.

[6] T. Tamura, Y. Maeda, M. Sekine, and M. Yoshida, "Wearable photoplethysmographic sensorspast and present," *Electronics*, vol. 3, no. 2, pp. 282–302, 2014.

[7] M. Nitzan, B. Khanokh, and Y. Slovik, "The difference in pulse transit time to the toe and finger measured by photoplethysmography," *Physiological measurement*, vol. 23, no. 1, p. 85, 2001.

[8] B. K. Ha, B. G. Kim, D. H. Kim, S. I. Lee, S. M. Jung, J. Y. Park, C. W. Lee, S. S. Kim, B. H. Kim, and I. J. Kim, "Relationships between brachial-ankle pulse wave velocity and peripheral neuropathy in type 2 diabetes," *Diabetes & metabolism journal*, vol. 36, no. 6, pp. 443–451, 2012.

[9] Y. Zheng, B. P. Yan, Y. Zhang, C. Yu, and C. C. Poon, "Wearable cuff-less ptt-based system for overnight blood pressure monitoring," in *Engineering in Medicine and Biology Society (EMBC), 2013 35th Annual International Conference of the IEEE*, pp. 6103–6106, IEEE, 2013.

[10] Y.-L. Zheng, B. P. Yan, Y.-T. Zhang, and C. C. Poon, "An armband wearable device for overnight and cuff-less blood pressure measurement," *Biomedical Engineering, IEEE Transactions on*, vol. 61, no. 7, pp. 2179–2186, 2014.

[11] S. Puke, T. Suzuki, K. Nakayama, H. Tanaka, and S. Minami, "Blood pressure estimation from pulse wave velocity measured on the chest," in *Engineering in Medicine and Biology Society (EMBC), 2013 35th Annual International Conference of the IEEE*, pp. 6107–6110, IEEE, 2013.

[12] C.-M. Chen, K. Onyenso, G.-Z. Yang, and B. Lo, "A multi-sensor platform for monitoring diabetic peripheral neuropathy," in *Wearable and Implantable Body Sensor Networks (BSN), 2015 IEEE 12th International Conference on*, pp. 1–6, IEEE, 2015.

[13] R. Wright and L. Keith, "Wearable technology: If the tech fits, wear it," *Journal of Electronic Resources in Medical Libraries*, vol. 11, no. 4, pp. 204–216, 2014.

[14] M. W. Wukitsch, M. M. T. Petterson, D. R. Tobler, and J. A. Pologe, "Pulse oximetry: analysis of theory, technology, and practice," *Journal of Clinical Monitoring*, vol. 4, no. 4, pp. 290–301, 1988.

[15] M. Berthelot, C.-M. Chen, G.-Z. Yang, and B. Lo, "Wireless wearable self-calibrated sensor for perfusion assessment of myocutaneous tissue," *BSN*, 2016.

[16] J. M. Bland and D. Altman, "Statistical methods for assessing agreement between two methods of clinical measurement," *The lancet*, vol. 327, no. 8476, pp. 307–310, 1986.

[17] J. Proença, J. Muehlsteff, X. Aubert, and P. Carvalho, "Is pulse transit time a good indicator of blood pressure changes during short physical exercise in a young population?," in *Engineering in Medicine and Biology Society (EMBC), 2010 Annual International Conference of the IEEE*, pp. 598–601, IEEE, 2010.

[18] F. Caird, G. Andrews, and R. Kennedy, "Effect of posture on blood pressure in the elderly.," *British Heart Journal*, vol. 35, no. 5, p. 527, 1973.

[19] A. Terént and E. Breig-åsberg, "Epidemiological perspective of body position and arm level in blood pressure measurement," *Blood pressure*, vol. 3, no. 3, pp. 156–163, 1994.