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Heart rate estimation using on-nail wearable photoplethysmography

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***Abstract*—Heart Rate (HR) measurements in current wearables are mostly derived from photoplethysmography (PPG). PPG signals have been measured at various locations on the body, however, to date, limited studies have investigated wearable, reflective mode, PPG signals from the finger- and toe- nails. Being rigid surfaces, they may provide comparatively motion robust measurements compared to sensors placed on flexible and stretchable skin. Here, we present an on-nail wearable PPG sensor to estimate HR from nail locations in motion-free and motion-present recordings. We compare to commercial electrocardiogram (ECG) and pulse oximeter (PO) units for 20 participants. PPG HR estimation demonstrated strong correlations with the ECG estimated HR, with a root mean square error of 1.6 beats per minute (bpm) and 2.2 bpm, for finger and toenail locations respectively. During motion these figures increased to 5.6 bpm and 12.8 bpm. No substantial difference in accuracy was found across the skin tone of participants. These results demonstrate the potential feasibility of HR monitoring from nail locations. With sensors placed, for example, inside a shoe, this may offer very discrete monitoring for long term applications.**

***Index Terms*—Nail photoplethysmography, electrocardiogram, heart rate, wearable sensors.**

I. Introduction

The growing interest in wearable technology has accelerated the development of long-term monitoring systems [1]. Nowadays, many smart wearables incorporate photoplethysmography (PPG) [2] for long term heart monitoring. Reflective PPG is a non-invasive optical technique used to determine Heart Rate (HR) by shining a light on a body surface, and measuring how much light is reflected. However, multiple studies have demonstrated that HR measurements from wearable PPG devices are often less accurate during physical activity [3]–[5]. This is due to the raw PPG signals being severely corrupted by Motion Artifacts (MA). These arise from multiple sources, principally displacement of the PPG sensor over the skin during motion. These MA may exhibit as missing or false beats, which result in inaccurate HR calculations.

Substantial literature has investigated signal processing approaches for removing this MA and allowing accurate HR estimates [3], [4], [6], [7]. We hypothesized that novel hardware and system approaches could also be used to tackle this challenge. In particular, that a system designed to sit on a hard and rigid surface of the body, such as a nail, would allow good HR estimates during motion.

To our knowledge, only a small number of studies have investigated on-nail wearable PPG before. [8] reported a 24 hour test using fingernail PPG while performing everyday tasks, finding that the fingernail PPG was comparable to a gold standard ECG when excluding periods of saturation due to MA. [9] utilized an ambient light cancellation circuit for a fingernail PPG unit to measure oxygen saturation (SpO2). However, it was not validated when MA was present. [10] presented a fingernail PPG sensor powered wirelessly using Near Field Communication (NFC) with a transmit coil up to 3 cm from the finger. Due to the need to place the power source close to the hand, the system was not suitable for continuous measurements. None of these studies consider the toenail as a sensing location, where the power source could potentially be embedded in the sole or upper fabric of a shoe, to allow long term, very socially discrete, monitoring.

In this paper we therefore present a new wirelessly powered PPG sensor, sized to sit on the thumb or big toe. We present a validation study, evaluating HR measurement accuracy during stationary and walking activities in a group of 20 individuals representing 5 different skin tones on the Fitzpatrick scale [11]. To our knowledge, this is the first reported evaluation of wearable PPG sensors on-nail across different skin tones, and while during motion, and the first to consider toenail locations.

II. On-nail PPG system design

Compared to other wearable PPG units, the main challenge for on-nail PPG is size. Our sensor, shown in Fig. 1, is made on an FR4 PCB, with a 7.9 mm radius to fit onto an average adult nail. The outer area is used for an NFC antenna, and the instrumentation uses 0402 packages to fit into the approximately 75 mm^2 inner area. The optical components are an infrared LED (APHHS1005F3C-70MAV, 950 nm) and photodetector (PD, TEMD7100X01). A micro-controller (µ-controller, Texas Instruments MSP430FR2311) contains a Trans-Impedance Amplifier (TIA), Smart Analog Combo (SAC), High-Pass and Low-Pass Filter (HPLPF), and an Analogue-to-Digital Converter (ADC). A Low Dropout Regulator (LDO) is included to regulate the power harvested

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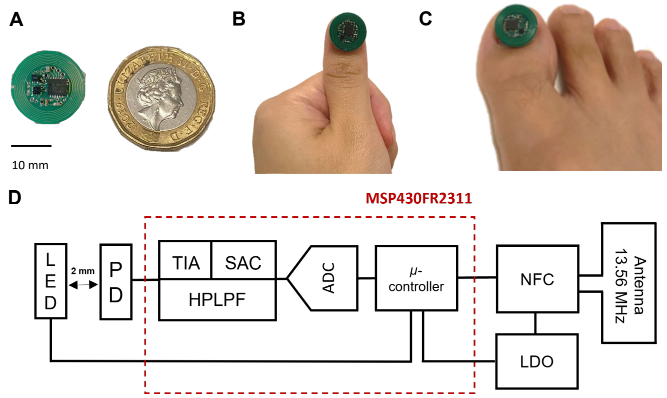

Fig. 1. (A) Example of the fabricated PPG sensor. A UK £1 coin is included for scale. (B), (C) The PPG sensor mounted on a finger- and toe- nail respectively. (D) PPG sensor architecture. Terms are defined in the main text.

from the NFC link to 2.5 V. Both the LED and PD are mounted on the reverse of the board, on the centre line, to allow reflective mode PPG recordings. 0.4–4 Hz hardware filtering is provided.

For wireless powering of the unit, and for transmitting data over an NFC link, we made a receiver unit using an off-the-shelf Adafruit PN532 NFC reader [12]. This receiver must be secured as close as possible (within 22 mm) to the PPG sensor to enable energy harvesting and stable data transmission via NFC, but otherwise the size and power constraints of the receiver unit are more relaxed and can be sized to fit on a standard shoe. All collected PPG data is stored on a microSD card in this receiver unit.

III. Validation Methodology

A. On-person experiment

Twenty healthy volunteers, 13 males and 7 females, age 30.6±5.7, of skin tone of 1–5 on the Fitzpatrick scale participated in a study to collect on-nail PPG. Exclusion criteria included health constrains (pregnancy/heart condition/eczema/skin allergies) and impeding nail conditions (nail polish/artificial nail). For device installation, a soft black adhesive tape was used to coat the bottom surface of the PPG device to facilitate conformal contact with the nail, and to prevent ambient light leaking into the PD. The PPG device was then covered with a fabric adhesive tape around the nail for a robust installation.

The experiment was divided into two parts: motion-free and motion-present. The motion-free part asked participants to be seated and not moving. PPG was recorded first from the fingernail, and then from the toenail, each for a 5 minute period. The motion-present part asked participants to walk on a treadmill at a 1 km/h pace for 5 minutes, and then the speed was increased to 3 km/h for another 5 minutes. This test was done only with the sensor at the toenail. While walking, the PPG device was installed on a toenail inside a shoe. The receiving device was installed on the outer front of the shoe, above the PPG sensor. For a robust installation, tape was used to wrap the receiver to the shoe to be as close as possible to the PPG sensor and to minimise motion interference in the receiver.

For comparison purposes, reference recordings were taken via two simultaneously connected commercial devices. Firstly, a single-channel, two-electrode, ECG recording was taken using an Actiwave Cardio (CamNtech, Cambridge, UK) with a sampling rate of 1024 Hz, and pre-gelled self-adhesive Silver-Silver Chloride (Ag/AgCl) electrodes as standard for ECG monitoring. These were placed on the upper chest. Secondly, a Pulse Oximeter (PO) device, a CMS50E (Contec, Suzhou, China), was installed on the middle fingernail or big toenail, on the opposite limb to our test sensor.

Approval of all experimental procedures and protocols was granted by the University of Manchester Research Ethics Committee, application no. 2023-15598-27148. Participants gave written informed consent before taking part.

B. Signal processing

Signal processing and data analysis were carried out using Matlab R2023a (The Mathworks, Natick, Massachusetts, USA). PPG signals were further bandpass filtered between 0.4–4 Hz to eliminate non-cardiac frequencies. Inter-beat intervals were then detected using the `findpeaks` function to count the number of peaks within a given window. Note that no dedicated artifact removal processing (other than basic filtering) is applied to our PPG. Our aim in the current work is to consider the performance of the new hardware/system approach, which can be combined with more sophisticated signal processing in future work. For ECG data, data was first filtered with a 50 Hz notch and then bandpass filtered between 0.4–100 Hz before detecting R peaks using the `findpeaks` function.

For both ECG and PPG, an HR estimate was produced every 2 s based on 8 s windows of data. This epoching approach has been widely used in other works such as [6], [7]. In each 8 s window, an estimated HR in beats per minute (bpm) was then calculated following the procedure in [6], [7] as

$$\text{Estiamted HR} = 60 \times \frac{n_{beats} - 1}{t_{last} - t_{first}} \quad (1)$$

where n_{beats} is the number of detected ECG or PPG beats, t_{last} is the time of the last beat in the window, and t_{first} the time of the first beat. The PO reference device outputted HR directly, therefore we directly use its reported HR every 2 s.

Performance, and accuracy, of the estimated heart rate from the new PPG device, compared to the reference ECG and PO devices, was assessed via: the Root-Mean-Squared-Error (RMSE) of the difference between the HR values in each window; the accuracy (defined as 100% minus the percentage difference between the mean HRs from each window); correlation coefficient (r); and Bland-Altman plots with mean bias and upper and lower Limits of Agreement (LoA).

IV. Results

Performance results are summarised in Table I. During motion-free use, the RMSE comparing the heart rate from the

TABLE I
COMPARISON OF HR MEASUREMENTS DURING MOTION-FREE AND MOTION-PRESENT RECORDINGS. SD: STANDARD DEVIATION.

	Estimated HR (Mean ± SD) (bpm)			PPG-ECG comparison				PPG-PO comparison			
	ECG	PO	PPG	RMSE (bpm)	Accuracy (%)	r	p-value	RMSE (bpm)	Accuracy (%)	r	p-value
Fingernail 0 km/h	70.2±2.2	69.4±3.1	69.9±2.9	1.6	99.6	0.98	0.36	3.3	99.3	0.93	0.20
Toenail 0 km/h	70.4±3.6	69.8±1.8	70.2±4.0	2.2	99.7	0.97	0.47	3.6	99.3	0.92	0.19
Toenail 1 km/h	77.3±2.9	47.4±0.1	76.9±7.3	5.6	99.6	0.88	0.25	35.9	61.6	0.13	<0.001
Toenail 3 km/h	84.1±1.9	49.0±0.4	77.0±1.9	12.8	93.5	0.62	<0.001	34.1	62.0	0.14	<0.001

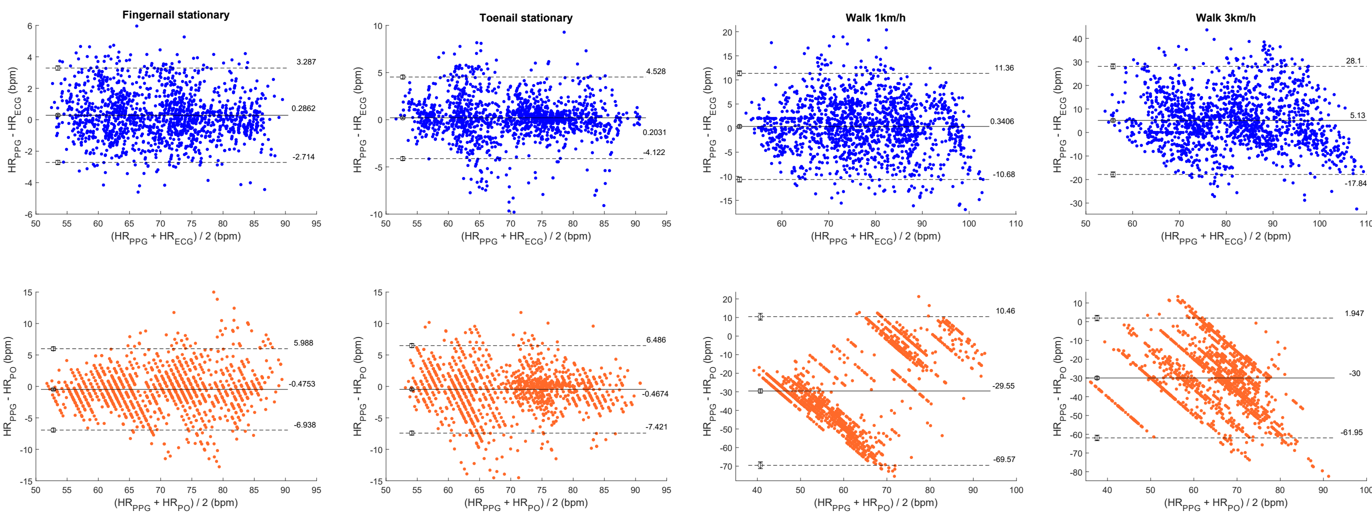

Fig. 2. Bland-Altman analysis between ECG (HR_{ECG}) and PPG (HR_{PPG}) derived HR (top: blue) and PO (HR_{PO}) and PPG (HR_{PPG}) derived HR (bottom: orange) across all modes of experiment.

new PPG unit to the ECG reference, was 1.6 bpm and 2.2 bpm for fingernail and toenail sensing sites respectively. The RMSE comparing PPG-PO was 3.3 bpm and 3.6 bpm at fingernail and toenail sites respectively. Overall, during the stationary setup, the mean HR taken from the PPG device was 99% accurate when compared to the value taken from the reference ECG and PO devices.

These errors increase when motion is present. The RMSE between PPG-ECG at a 1 km/h walking pace was 5.6 bpm and 12.8 bpm at 3 km/h (sensor at the toenail). In contrast, the PPG-PO error was much higher at 34 bpm, suggesting inaccurate measurements from the PO unit, as would be expected during motion for a current commercial PO units. As seen in Table I, we found high correlations between HR estimates from the new PPG and reference ECG, with $r > 0.88$ until faster walking was present. In the PPG-PO case, a high correlation was found only in the motion-free setup, with $r > 0.9$. However, the p-values are high in most cases.

As an alternative visualization of performance, the Bland-Altman plot in Fig. 2 shows the differences in HR values between PPG-ECG and PPG-PO. In motion free cases, the bias for PPG-ECG was 0.3 bpm, with LoA 3.3, −2.7 bpm, for the fingernail; and bias 0.2 bpm, LoA 4.5, −4.1 bpm for the toenail. During 1 km/h walking, measured at the toenail, these increase to bias 0.3 bpm, LoA 11.4, −10.7 bpm, and at 3 km/h pace to bias 5.1 bpm, LoA 28.1, −17.8 bpm. In contrast, the LoA for the PPG-PO during motion are poor, again suggesting inaccurate measurements from the PO unit during motion.

Studies in [13], [14] report that PPG measurements may be less accurate on darker skin tones than on lighter skin tones due to light absorption by melanin. In this study, we compared the RMSE of average HR from the fingernail and toenail for different skin tones during the motion-free setup, with results in Fig. 3. For our new sensor on the nail we observed no substantial differences in individual RMSE. Rather, the location of the measurement (fingernail vs. toenail) was more influential on the estimated HR accuracy.

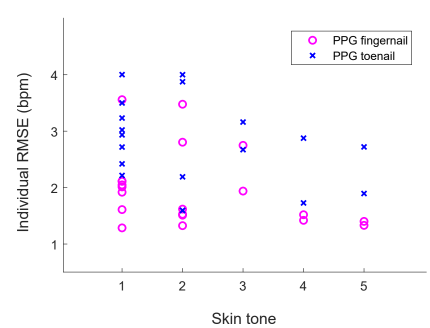

Fig. 3. Per-individual HR RMSE across Fitzpatrick skin tones 1–5 during motion free setup. Calculated as the RMSE of average HR between the ECG and PPG on fingernail and toenail.

V. Discussion

PPG signals collected while stationary showed very high accuracy compared to the gold standard reference devices. This demonstrates the feasibility of PPG and HR monitoring at both sites, although the error is consistently larger at the toenail. This may reflect the volumetric nature of a PPG measurement, with the foot being a long way from the heart, and there being many places where the blood flow may be influenced by the physiology present. To our knowledge this is the first study to consider whether HR estimation from toenail PPG is possible during motion. Correlations between PPG and ECG estimated HR of 0.88 for 1 km/h walking and 0.62 for 3 km/h walking were found, although only the latter was below a $p = 0.01$ statistical significance threshold. In terms of RMSE, these corresponded to 5.6 bpm and 12.8 bpm respectively.

We put these values in context via the Bland-Altman analysis. For the 1 km/h case our LoA were 11.4 and -10.7 bpm. [15] reported LoA values of 7.3 and -9.9 bpm when comparing HR estimation between ECG and an Apple Watch, when stationary and in motion. [16] compared HR estimates from four commercial wearable PPG sensors to ECG during walking/running on treadmill. Among all the devices, the Apple Watch and MioFuse had the lowest LoA, 29, -27 bpm, in contrast to our LoA of 28.1, -17.8 bpm during the 3 km/h case. Scope for improvement is thus present, but recall that at present we do not apply processing other than band filtering to the collected PPG. Even without advanced signal processing, our performance is comparable, and future work can consider applying signal processing to improve this further. Our results evidence that toenail-based HR estimation, inside a shoe, for discrete, long term, monitoring is feasible. In general, we obtained poor HR estimates from the reference PO device used, which we attribute to the PO unit fitting poorly on to the surface of a toenail.

We did not find substantial differences in HR accuracy across skin tones. This is consistent with several studies which also found no statistically significant differences in wearable HR measurement accuracy across skin tones [17], [18], although other studies contradict this, [13], [14]. Healthy nails are generally flesh-coloured, with white tips. However, there can be changes in the colour of the nail, for example yellowish or greyish colours, which do not depend on skin tone but on the health of the nail itself. The condition of the nail (either smooth or bumpy) and any surface treatments (such as nail polish) may also have substantial effects on the collected signal. All these factors should be investigated further in future work.

VI. Conclusions

This work has demonstrated the feasibility of an on-nail wearable PPG system to estimate HR from fingernail and toenail locations. The PPG sensor is accurate to within 2.2 bpm in stationary situations. During motion, measurement accuracy decreases, but is still in-line with that from commercial PPG units. To our knowledge this is the first demonstration of toenail-based HR monitoring during motion. We suggest that the toe mounted location may allow socially discrete long-term monitoring with receiver electronics mounted inside a shoe.

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