Wearable Photoplethysmography: Current Status and Future Challenges

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Abstract

This paper provides an update on the current status and future challenges in the field of wearable photoplethysmography, an optical sensing technology which is widely used in wearables such as smartwatches. It builds on 'The 2023 Wearable Photoplethysmography Roadmap', an article in which 51 leading researchers provided their insights into the key research required to realise the full potential of wearable photoplethysmography. Firstly, this paper presents the findings of the Roadmap. Then, further developments in the field not covered in the Roadmap are discussed, including conducting large-scale studies with wearables and advances in signal processing and machine learning. Finally, reflections are provided on the process of co-ordinating a Roadmap article.

1. Introduction

Smart wearables provide an unprecedented opportunity to monitor health and fitness unobtrusively in daily life. Devices such as smartwatches, smart bands, and smart rings use the technique of photoplethysmography to measure the pulse wave, from which a wealth of physiological information can be derived [1]. Consequently, much research focuses on developing wearable photoplethysmography technologies for health and fitness applications, including screening for cardiovascular disease, detection of heart arrhythmias, cuffless blood pressure monitoring, and assessing sleep quality.

This paper provides an update on the current status and future challenges in the field of wearable photoplethysmography. It builds on 'The 2023 Wearable Photoplethysmography Roadmap', an article in which 51 leading researchers in the field of photoplethysmography provided their insights into the key research required to realise the full potential of wearable photoplethysmography. This paper starts by summarising the findings of the Roadmap, then highlights further developments in the field not covered in the Roadmap, and finally provides reflections on the process of co-ordinating a Roadmap article.

2. The 2023 Wearable Photoplethysmography Roadmap

The '2023 Wearable Photoplethysmography Roadmap' explores the current status of wearable photoplethysmography and future challenges to realise the full potential of this technology [2]. It includes contributions from over 50 experts. The Roadmap was intended to help guide future research and development in the field, focusing on the challenges ahead and their potential solutions. We now provide a brief summary of the areas explored within the document, the themes emerging across the document, and the key challenges identified and their potential solutions. These topics are covered in further depth in the Introduction to the Roadmap.

2.1. Areas explored

The Roadmap covers 24 topics across four areas:

- **Sensor design:** Innovative photoplethysmography sensor designs are being developed, including flexible tattoo sensors, in-ear sensors, and multi-wavelength photoplethysmography sensors.
- **Signal processing:** Photoplethysmography signal processing continues to advance, focusing on the optimal conditioning of the PPG signal, especially against the challenges of movement artefact, and also the utilisation of the signal for applications such as blood pressure, respiratory and sleep monitoring.
- **Applications:** Several potential applications of wearable photoplethysmography are described, from the detection of atrial fibrillation (AF) to mental health assessment.
- **Research directions:** Key directions include designing device validation protocols, identifying sources of inaccuracy, and investigating alternative sensing technologies.

2.2. Themes emerging

Several key themes emerged from the Roadmap:

- **Expanding functionality:** The functionality of wearable photoplethysmography devices is expanding with the ability to monitor novel parameters such as blood pressure,

ISSN: 2325-887X DOI: 10.22489/CinC.2023.076

oxygen saturation, and even detailed respiratory metrics. The PPG signal has also been explored for the assessment of vascular health and mental health (*i.e.* stress).

- **Optimising sensor design:** Key design decisions include: the anatomical site of the sensor, the optimal topology of the optical components (sources and detectors), and the wavelength(s) of light used.
- **Approaches to signal processing:** A wide range of photoplethysmogram (PPG) signal processing techniques have been proposed, and it is not yet clear which perform best, particularly across different applications.
- **Identifying potential applications:** New applications for wearable photoplethysmography are being identified, aided by the expanding functionality of the technology.
- **Gaining trust:** Using wearable photoplethysmography devices to their full potential will require the trust of multiple stakeholders including clinicians, policy makers, and most importantly device users.

2.3. Challenges and solutions identified

Several key challenges and potential solutions emerged from the Roadmap:

- **Signal quality:** The PPG is highly susceptible to noise. Approaches to handle noise range from optimising sensor design, to developing signal processing techniques to delineate low quality periods and recover noise-free signals.
- **Signal processing resources:** The development of signal processing algorithms is greatly aided by open datasets and code. Wearable devices which provide raw PPG signals provide opportunity to acquire datasets in daily life.
- **Device validation:** Agreed processes for device validation are being developed to provide a comprehensive understanding of real-world performance across subjects with different characteristics.
- **Sources of inaccuracy:** Several potential sources of inaccuracy in wearable photoplethysmography devices have been identified. Work is ongoing to identify further sources and mitigate against them.
- **Equity:** It is important to be mindful of the equity of access to devices and their performance. Key considerations are the cost of devices and their performance in subjects with different characteristics (*e.g.* skin type).
- **Best practices:** Best practices could be established across: sensor design; signal quality assessment; signal processing algorithms; benchmark datasets; measurement protocols; and standardised evaluation protocols.

3. Further developments in the field

This section provides an update on recent developments in the field, and brief introductions to some potentially important topics not covered in depth in the Roadmap.

Wearable devices provide an unparalleled opportunity to perform large-scale, low-cost studies of health and physiology. Until the widespread use of consumer wearables, such studies were typically performed through established research infrastructures, such as physical activity studies conducted through UK Biobank [3]. The extensive use of connected consumer wearables facilitates large-scale studies, including both observational and interventional studies. This approach was pioneered in the Apple Heart Study [4], and more recently used with Huawei, FitBit [5], and Oura Ring data [6].

The promise of consumer smartwatches for detecting an irregular pulse indicative of AF has already been shown in large-scale interventional studies [4, 5]. Some smartwatches can now record an electrocardiogram (ECG) on demand at the wrist, which could potentially provide opportunity to not only detect an irregular pulse from the PPG, but also to confirm an AF diagnosis via ECG recording. This approach is being investigated in the Heartline study [7], and is also being used in clinical devices [8].

Machine learning is now widely used for PPG analysis. In the field of pulse wave analysis, feature selection techniques are being used to identify the most relevant pulse wave features to act as model inputs [9]. In the field of deep learning, there is a need to identify the best class(es) of neural networks for PPG analysis, and the best architectures. There is increasing interest in quantifying the uncertainties associated with machine learning-based PPG analyses: this topic is being investigated in QUMPHY, a consortium project funded by the European Partnership on Metrology. Finally, new strategies are being developed to handle the noisy labels sometimes present in large, real-world PPG datasets [10].

PPG signal processing remains a highly active area of research. The fundamental tasks of heart rate estimation and beat detection were not covered in the Roadmap, and the reader is referred to [11] and [12] for further details of these techniques. Recent advances in beat detection algorithms include improving their performance in AF [13] and improving their computational efficiency [14]. In the field of PPG signal quality assessment there is a growing consensus that different levels of signal quality are required for different PPG analysis tasks [15]. A growing number of open resources are available to aid research into PPG signal processing. The Aurora-BP dataset contains simultaneous PPG, electrocardiogram, accelerometry, and tonometry recordings acquired from hundreds of participants in laboratory conditions and daily life [16]. Python toolboxes for PPG analysis are improving, with the release of the *pyPPG* toolbox [14, 17], and increased functionality of the *neurokit2* toolbox [18].

Pulse oximetry has now been incorporated into many consumer wearables. Whilst concerns remain over differences in the accuracy of pulse oximeters across different skin types [19], a recent study did not find such differences in consumer smartwatches [20].

Finally, a few further updates. First, standard protocols are being developed to validate wearables. The Roadmap covered validation for blood pressure, and in addition, the Interlive network has recently developed protocols to validate step counts, heart rate, energy expenditure, and maximal oxygen consumption (*e.g.* [21]). Second, the potential use of wearables to detect viral infections remains of great interest following the COVID-19 public health emergency [22]. Third, recent work adds to our understanding of the merits of different anatomical sites for photoplethysmography sensors, including comparisons of finger and wrist signals [23], and the rise of hearables [24].

4. Co-ordinating a Roadmap article

In this section I (PHC) reflect on the process of co-ordinating a Roadmap article. In recent years IOP Publishing have published Roadmap articles in some of their journals [25], and this option was extended to *Physiological Measurement* in 2021. Despite our previous best efforts [1, 26], I thought a comprehensive overview of the field of wearable photoplethysmography was still required, particularly one providing clear directions for future research. Given the size of the field, I thought this would be best achieved by bringing together experts in a range of topics. A Roadmap article appeared appropriate as it allows multiple authors to contribute their perspectives, and focuses on the most pressing research directions. I was encouraged by the publisher's enthusiasm for such articles, and by the success of some previous Roadmaps (*e.g.* [27]).

The process of co-ordinating the Roadmap consisted of the following steps. First, I identified potential topics for inclusion. Second, I searched for experts on each topic, based on the literature. Third, experts were invited to contribute and were supplied with author guidelines. Fourth, contributions internally reviewed by myself and another co-author. Fifth, authors revised their contributions in response to feedback. Finally, the manuscript was collated and submitted for external peer review.

Reflecting on the process, there were several rewarding aspects, and a few lessons learnt. The early stages of the process helped me deepen my understanding of the field, and put me in contact with people I believed to be experts in the field. These unsolicited communications were almost always very well received, and I was struck by people's willingness to contribute. Inevitably, my role as co-ordinator will have introduced some bias into the choice of topics and authors. For instance, I was disappointed to realise that there are no authors from Africa or South America, nor any from any low- or middle-income countries. Furthermore, the authors are primarily from academic and engineering backgrounds, with fewer from industrial or clinical backgrounds. I think that the contributions of those working in industry and clinical practice greatly enhanced the Roadmap, and in the future I would be interested in including patient views. The internal peer review process was inspired by that taken when preparing a recent textbook [28]. I was grateful for the willingness of co-authors to perform internal reviews, which greatly improved the manuscript. A few further comparisons between Roadmaps and textbooks are warranted. This Roadmap article has different goals to a textbook: whilst it introduces topics in a manner suitable for beginners, it does not provide a comprehensive introduction, and does not describe much background theory (for this the reader is referred to [29]). Furthermore, it focuses primarily on the future of the field, rather than work to date. The publication process was more similar to that of a traditional journal article than that of a textbook, and we were able to meet open-access fees through the usual journal funding routes, avoiding the typically larger open-access fees associated with textbooks.

Finally, resources used when co-ordinating the Roadmap are available for future Roadmap co-ordinators [30].

5. Conclusion

The future is bright for wearable photoplethysmography: it has potential to provide a wealth of physiological information with numerous applications in health, fitness, and wellbeing. However, there is much work to be done to realise the full potential of wearable photoplethysmography. The '2023 Wearable Photoplethysmography Roadmap' provides valuable directions for future work across many topics [2], and additional important topics have been presented in this article. The field continues to progress rapidly, aided by healthy interest from academia, industry, and clinical practice.

Acknowledgments

This work was supported by the British Heart Foundation (BHF) [grant number FS/20/20/34626], and Innovate UK [grant number 10091955]. The project (22HLT01 QUMPHY) has received funding from the European Partnership on Metrology, co-financed from the European Union's Horizon Europe Research and Innovation Programme and by the Participating States. Several ideas and some content are reproduced from [2] under CC BY 4.0.

Conflicts of Interest

PHC is on the Executive Editorial Board for *Physiological Measurement*. His attendance at Computing in Cardiology 2023 was partially funded by IOP Publishing.

References

[1] P. H. Charlton and V. Marozas, "Wearable photoplethysmography devices," in *Photoplethysmography*, P. Kyriacou and J. Allen, Eds. Elsevier, 2022, pp. 401–439.

[2] P. Charlton *et al.*, "The 2023 wearable photoplethysmography roadmap," *Physiological Measurement [in press]*, 2023.

[3] A. Doherty *et al.*, "Large scale population assessment of physical activity using wrist worn accelerometers: The UK biobank study," *PLoS ONE*, vol. 12, no. 2, pp. 1–14, 2017.

[4] M. V. Perez *et al.*, "Large-scale assessment of a smartwatch to identify atrial fibrillation," *New England Journal of Medicine*, vol. 381, no. 20, pp. 1909–1917, 2019.

[5] S. A. Lubitz *et al.*, "Detection of atrial fibrillation in a large population using wearable devices: The Fitbit Heart Study," *Circulation*, vol. 146, pp. 1415–1424, 2022.

[6] A. R. Willoughby *et al.*, "Country differences in nocturnal sleep variability: Observations from a large-scale, long-term sleep wearable study," *Sleep Medicine*, vol. 110, pp. 155–165, 2023.

[7] C. M. Gibson *et al.*, "Does early detection of atrial fibrillation reduce the risk of thromboembolic events? Rationale and design of the Heartline study," *American Heart Journal*, vol. 259, pp. 30–41, 2023.

[8] T. Halkola *et al.*, "Using wearable photoplethysmography for detecting atrial fibrillation in ambulatory conditions," in *Computing in Cardiology 2023*, 2023.

[9] C. Aguet *et al.*, "Blood pressure monitoring during anesthesia induction using PPG morphology features and machine learning," *PLOS ONE*, vol. 18, no. 2, p. e0279419, 2023.

[10] C. Ding *et al.*, "Learning from alarms: a novel robust learning approach to learn an accurate photoplethysmography-based atrial fibrillation detector using eight million samples labeled with imprecise arrhythmia alarms," in *Computing in Cardiology 2023*, 2023.

[11] D. Biswas *et al.*, "Heart rate estimation from wrist-worn photoplethysmography: A review," *IEEE Sensors Journal*, vol. 19, no. 16, pp. 6560–6570, 2019.

[12] P. H. Charlton *et al.*, "Detecting beats in the photoplethysmogram: benchmarking open-source algorithms," *Physiological Measurement*, vol. 43, no. 8, p. 085007, 2022.

[13] D. Han *et al.*, "A real-time PPG peak detection method for accurate determination of heart rate during sinus rhythm and cardiac arrhythmia," *Biosensors*, vol. 12, no. 2, p. 82, 2022.

[14] M. Goda, P. Charlton, and J. Behar, "Robust peak detection for photoplethysmography signal analysis," in *Computing in Cardiology 2023*, 2023.

[15] S. Moscato *et al.*, "Wrist photoplethysmography signal quality assessment for reliable heart rate estimate and morphological analysis," *Sensors*, vol. 22, no. 15, p. 5831, 2022.

[16] R. Mieloszyk *et al.*, "A comparison of wearable tonometry, photoplethysmography, and electrocardiography for cuffless measurement of blood pressure in an ambulatory setting," *IEEE Journal of Biomedical and Health Informatics*, vol. 26, no. 7, pp. 2864–2875, 2022.

[17] J. A. Behar *et al.*, "PhysioZoo: The open physiological biomarkers resource," in *Computing in Cardiology 2023*, 2023.

[18] D. Makowski *et al.*, "NeuroKit2: A Python toolbox for neurophysiological signal processing," *Behavior Research Methods*, vol. 53, no. 4, pp. 1689–1696, 2021.

[19] R. Al-Halawani *et al.*, "A review of the effect of skin pigmentation on pulse oximeter accuracy," *Physiological Measurement*, vol. 44, p. 05TR01, 2023.

[20] Y. Jiang *et al.*, "Investigating the accuracy of blood oxygen saturation measurements in common consumer smartwatches," *PLOS Digital Health*, vol. 2, no. 7, p. e0000296, Jul. 2023.

[21] J. M. Mhlen *et al.*, "Recommendations for determining the validity of consumer wearable heart rate devices: expert statement and checklist of the INTERLIVE Network," *British Journal of Sports Medicine*, vol. 55, no. 14, pp. 767–779, 2021.

[22] C. J. Goergen *et al.*, "Detection and monitoring of viral infections via wearable devices and biometric data," *Annual Review of Biomedical Engineering*, vol. 24, no. 1, pp. 1–27, 2022.

[23] W. Wu *et al.*, "Finger versus wrist photoplethysmography signals: Implications for wearable blood pressure monitoring," in *IEEE Conference on Artificial Intelligence*, 2023, pp. 124–125.

[24] K. Azudin *et al.*, "The principles of hearable photoplethysmography analysis and applications in physiological monitoring-a review," *Sensors*, vol. 23, no. 14, p. 6484, 2023.

[25] S. R. Cherry and H. Young, "Launching our new Roadmap articles," *Physics in Medicine & Biology*, vol. 65, no. 21, p. 210301, 2020.

[26] P. H. Charlton *et al.*, "Wearable Photoplethysmography for Cardiovascular Monitoring," *Proceedings of the IEEE*, vol. 110, no. 3, pp. 355–381, 2022.

[27] J. Ma *et al.*, "The 2021 battery technology roadmap," *Journal of Physics D: Applied Physics*, vol. 54, no. 18, p. 183001, 2021.

[28] MIT Critical Data, *Secondary Analysis of Electronic Health Records*. Springer International Publishing, 2016.

[29] P. Kyriacou and J. Allen, Eds., *Photoplethysmography: Technology, Signal Analysis, and Applications*. Elsevier, 2021.

[30] P. H. Charlton, "Resources for co-ordinating a Roadmap article," *Zenodo*, 2023, https://doi.org/10.5281/zenodo.8360151.

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