

Evaluating the Reliability of SpO₂ and BPM Readings in Commercial Smartwatches Compared to a Standard Oximeter

Kusnanto Mukti Wibowo¹, Royan Royan¹, Abdul Latif¹, Fani Susanto², Fatiatun³, Rudi Irmawanto⁴, and Norhidayah Che Ani^{5,6}

¹Department of Medical Electronics Engineering Technology, Universitas Muhammadiyah Purwokerto, Purwokerto, Indonesia

²Department of Radiologic Imaging Technology, Universitas Muhammadiyah Purwokerto, Purwokerto, Indonesia

³Department of Physics Education, Universitas Sains Al-Qur'an, Wonosobo, Indonesia

⁴Department of Electrical Engineering, Universitas Muhammadiyah Surabaya, Surabaya, Indonesia

⁵Faculty of Electrical and Electronic Engineering, Universiti Tun Hussein Onn Malaysia (UTHM), 86400 Parit Raja, Batu Pahat, Johor, Malaysia

⁶Microelectronics and Nanotechnology-Shamsudin Research Centre (MiNT-SRC), Universiti Tun Hussein Onn Malaysia (UTHM), 86400 Parit Raja, Batu Pahat, Johor, Malaysia

ABSTRACT

The advancement of wearable technology has enabled commercial smartwatches to monitor vital health parameters such as blood oxygen saturation (SpO₂) and heart rate (BPM). This study aimed to evaluate the accuracy of SpO₂ and BPM readings from three commercial smartwatches: Realme C2 Pro, Oraimo 2 Plus OSW-32N, and Haylou LS02 Pro by comparing them to a standard medical-grade oximeter (Beurer PO40). A total of 34 participants were recruited, representing a range of skin tones identified using the Fitzpatrick Skin Type Scale (Types I–V). Statistical analyses, including Pearson's correlation and Bland-Altman plots, were used to assess the relationship and agreement between devices. Results showed that the Realme C2 Pro provided the highest accuracy, with 99.58% for SpO₂ and 98.515% for BPM, while the Haylou LS02 Pro showed the lowest accuracy at 99.24% for SpO₂ and 97.29% for BPM. Bland-Altman analysis revealed small biases and narrow limits of agreement, indicating that the smartwatches produced readings closely aligned with those of the medical device. Despite minor discrepancies, all smartwatches demonstrated strong potential for health monitoring applications. The discussion highlights factors influencing measurement accuracy, including sensor quality, algorithm performance, and user-specific variables such as skin tone. These findings support the role of smartwatches as accessible tools for early health detection and continuous monitoring. Although not intended to replace clinical instruments, properly optimized smartwatches can complement healthcare systems by enabling timely interventions and enhancing disease management.

PAPER HISTORY

Received March 20, 2025

Revised Mei 20, 2025

Accepted 13 June, 2025

Published June 27, 2025

KEYWORDS

Accuracy;
SpO₂;
bpm;
smartwatch;
oximeter

CONTACT:

kusnantomukti@gmail.com

royan@ump.ac.id

abdulaltif@ump.ac.id

fanisusanto@ump.ac.id

fatia2011physic@gmail.com

norhidayah1718@gmail.com

rudi.irmawanto@ft.um-surabaya.ac.id

1. INTRODUCTION

The development of wearable technology, particularly smartwatches, has enabled users to monitor various health parameters in real-time, including blood oxygen saturation (SpO₂) and heart rate (BPM). Commercial smartwatches are increasingly popular as self-monitoring health tools due to their accessibility, portability, and continuously improving features [1]–[7]. However, the accuracy of these devices remains a subject of debate, especially when compared to standard medical devices such as conventional oximeters [8] [9]. Conventional oximeters, widely used in clinical settings, utilize the principle of photoplethysmography (PPG) to measure

SpO₂ with high accuracy [10]–[16]. Although many commercial smartwatches also rely on PPG sensors, discrepancies in sensor placement, algorithm design, and external influences—such as user motion or skin tone—can lead to inconsistent readings [17]–[22]. These limitations raise concerns about the clinical reliability of consumer-grade wearable devices, especially in sensitive contexts such as hypoxia detection [23]–[25]. Several recent studies have evaluated the precision and validity of smartwatches in comparison with standard pulse oximeters, with results showing mixed outcomes depending on the model and context. For instance, Rafi et al. [26] demonstrated that commercial smartwatches

Corresponding author: Kusnanto, kusnantomuktiwibowo@ump.ac.id, Department of Medical Electronics Engineering Technology, Universitas Muhammadiyah Purwokerto, Purwokerto, Indonesia.

DOI: <https://doi.org/10.35882/teknokes.v18i2.33>

Copyright © 2025 by the authors. Published by Jurusan Teknik Elektromedik, Politeknik Kesehatan Kemenkes Surabaya Indonesia. This work is an open-access article and licensed under a Creative Commons Attribution-ShareAlike 4.0 International License ([CC BY-SA 4.0](https://creativecommons.org/licenses/by-sa/4.0/)).

could detect short-term hypoxemia comparably to medical-grade oximeters, while other research noted error rates exceeding 5% in some models [27]–[30]. Jiang et al. also emphasized variability in blood oxygen saturation readings across different smartwatch brands, which can compromise their usefulness in medical decision-making [2]. Beyond accuracy, the increasing adoption of wearable health technologies is driven by growing public interest in proactive health management. Individuals with chronic conditions such as respiratory or cardiovascular disorders frequently rely on wearable devices for continuous monitoring outside clinical settings [31], [32]. However, when devices produce inaccurate readings, users may misinterpret their health status, potentially leading to delayed or inappropriate actions [33]. Consequently, validation of these tools under real-world conditions becomes imperative. Another challenge is the dynamic nature of smartwatch systems—firmware updates [34], changes in data processing algorithms [35], [36], and model-specific features all contribute to inconsistencies in measurement outcomes over time [37][38]. Studies conducted by Shapiro et al. and Sharma et al. highlight how massive datasets and IoT-based frameworks can be used to enhance monitoring

capabilities, while also revealing the need for standardization and accuracy assurance [39], [40].

Therefore, ongoing performance evaluations across different devices are essential for maintaining credibility in health monitoring contexts. Considering these factors, this study aims to analyze the accuracy of SpO₂ and BPM measurements in three different commercial smartwatches by comparing them with a conventional oximeter as the reference standard. The findings of this study are expected to provide insights into the reliability of smartwatches for health monitoring and assist users in selecting devices best suited to their needs. Furthermore, this research may inform clinicians, developers, and policymakers about the potential and limitations of wearable health technology in supporting both clinical and self-care applications.

2. MATERIALS AND METHOD

This study employed a comparative analysis approach to evaluate the accuracy of SpO₂ and BPM measurements between three commercial smartwatches and a conventional oximeter. The three commercial smartwatches evaluated in this study were Realme C2 Pro, Oraisimo 2 Plus OSW-32N, and Haylou LS02 Pro as shown in Figure 1 and full specification were displayed on Table 1. A conventional oximeter, the Beuer PO40, was used as the reference standard.,

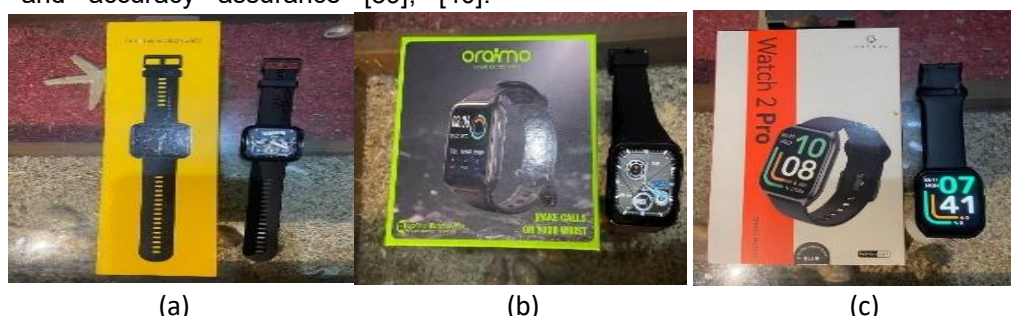


Fig. 1. Smartwatch used in this study: (a) Realme C2 pro, (b) Oraisimo 2plus OSW-N, and (c) Haylou LS02 Pro

Table 1. Specification of the smartwatches

	Realme	Oraisimo	Haylou
Type	C2 Pro	2 plus OSW-N	LS02 Pro
weight	40 gr	43 gr	38 gr
LCD size	1,75"	1,69"	1,85"
Waterproof	IP68	IP68	IP68
Battery	390 mAh	300 mAh	260 mAh
Bluetooth connection	v5.0	v5.1	v5.0
Sport mode	90 sport modes	24 sport modes	100 workout modes
Health features	• SpO2 monitoring • bpm monitoring • sleep detection • calories burn counter • steps counter • VO2Max test	• SpO2 monitoring • bpm monitoring • respiratory rate monitoring	• SpO2 monitoring • bpm monitoring • smart sleep monitoring

All smartwatches were tested in their factory default configurations, with firmware confirmed to be the latest available at the time of data collection. No firmware updates occurred during the measurement period. This ensured that variations in software versions would not introduce bias during data acquisition

A total of 34 participants (both male and female) aged 18–41 years were recruited. Participants represented various skin tones, categorized using the Fitzpatrick Skin Type Scale (Types I–V). Although skin tone distribution was documented, subgroup statistical analysis was not conducted due to the limited number of participants in each category.

Before data collection, participants were asked to sit calmly for five minutes. During measurement, their hands rested on a table, in a stable, well-lit environment with normal room temperature. Participants were instructed to avoid movement to reduce artifacts in the photoplethysmographic (PPG) signals. SpO₂ and BPM readings were simultaneously recorded from each smartwatch and the Beurer PO40 oximeter. Measurements were taken five times at one-minute intervals. The average of the five readings was used for further analysis to reduce measurement variability.

The accuracy of the smartwatch measurements was evaluated using the Bland-Altman plot to assess the agreement between the smartwatch readings and the reference oximeter. The mean differences and limits of agreement (LoA) were calculated to determine the degree of bias and variability in the smartwatch measurements. The mean difference served as an indicator of bias, while the limits of agreement were established at ± 1.96 standard deviations from the mean difference to determine the extent of variability between devices [41] [42].

The limits of agreement are calculated as:

upper limit = $\bar{d} + 1,96. \sigma$

lower limit = $\bar{d} - 1,96. \sigma$

Where is $\bar{d}$ = mean of all d_i (d_i represent the difference between two measurements for subject i)

σ = standard deviation of the differences d_i

3. RESULTS

A total of 34 participants were involved in the study, representing a range of skin tone levels based on the Fitzpatrick skin type scale (Types I–V). The distribution of participants across skin tone categories is shown in Figure 2. The majority of participants were classified within mid-range skin tones, with 11 participants (32.4%) at Level III, 10 participants (29.4%) at Level II, and 9 participants (26.5%) at Level IV. The remaining participants included 4 individuals (11.8%) with Level V skin tone and only 1 individual (2.9%) with Level I skin tone.

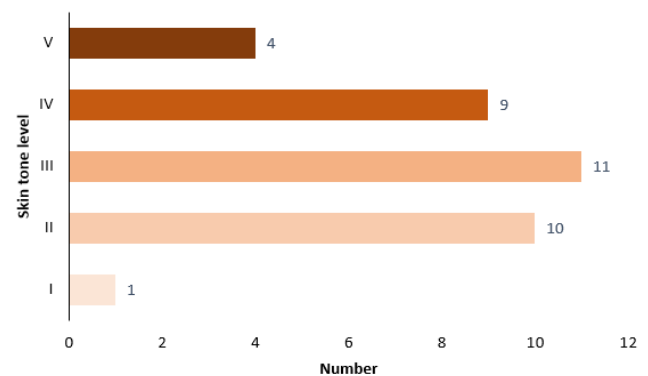


Fig. 2. Skin tone level of samples

Figure 3 shows a strong positive correlation of smartwatch and commercial oximeters when assessing bpm measurements with $r = 0.96$ for Haylou and Oraimo and $r = 9.99$ for Realme.

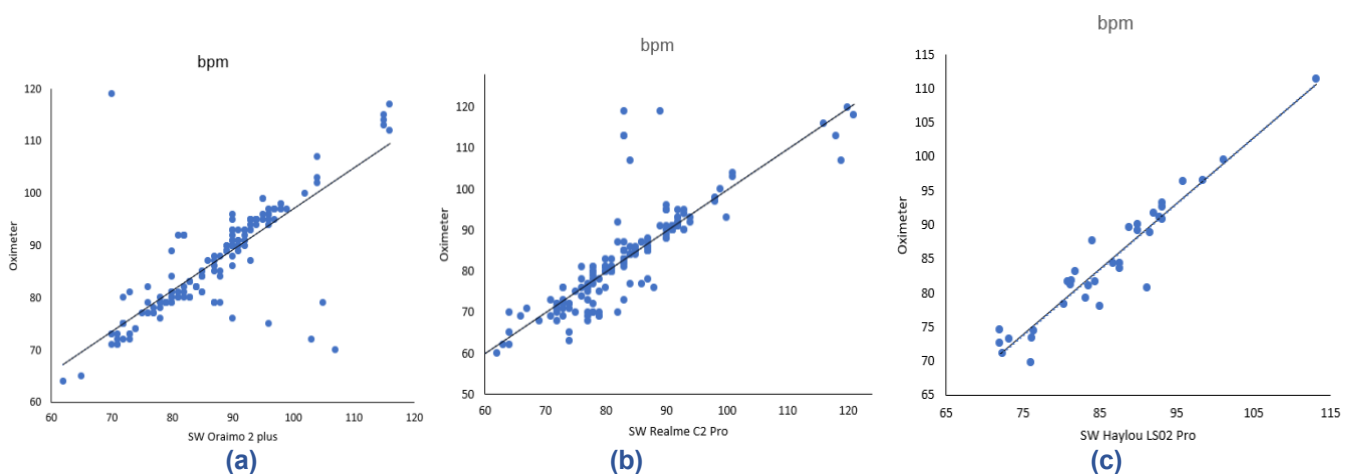


Fig. 3. Correlation plot of bpm using smartwatches: (a) Realme C2 Pro, (b) Oraimo 2 Plus OSW-32N and (c) Haylou LS02 Pro

Corresponding author: Kusananto, kusnantomuktiwibowo@ump.ac.id, Department of Medical Electronics Engineering Technology, Universitas Muhammadiyah Purwokerto, Purwokerto, Indonesia.

DOI: <https://doi.org/10.35882/teknokes.v18i2.33>

Copyright © 2025 by the authors. Published by Jurusan Teknik Elektromedik, Politeknik Kesehatan Kemenkes Surabaya Indonesia. This work is an open-access article and licensed under a Creative Commons Attribution-ShareAlike 4.0 International License ([CC BY-SA 4.0](https://creativecommons.org/licenses/by-sa/4.0/)).

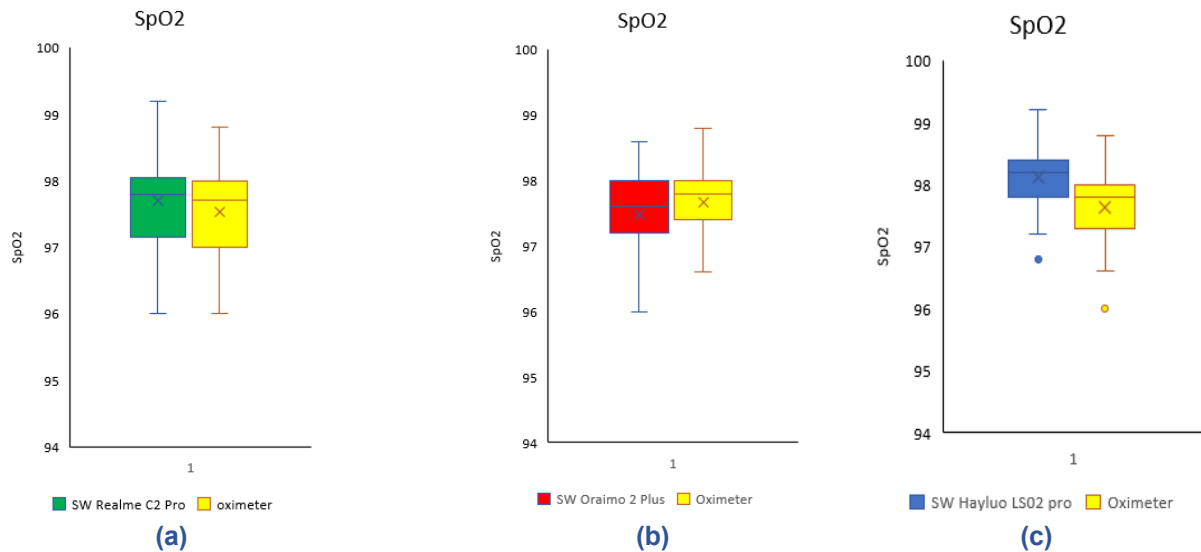


Fig. 4. Comparison of smartwatches and oximeter of SpO2: (a) Realme C2 Pro, (b) Oramo 2 Plus, and (c) Haylou LS02 Pro

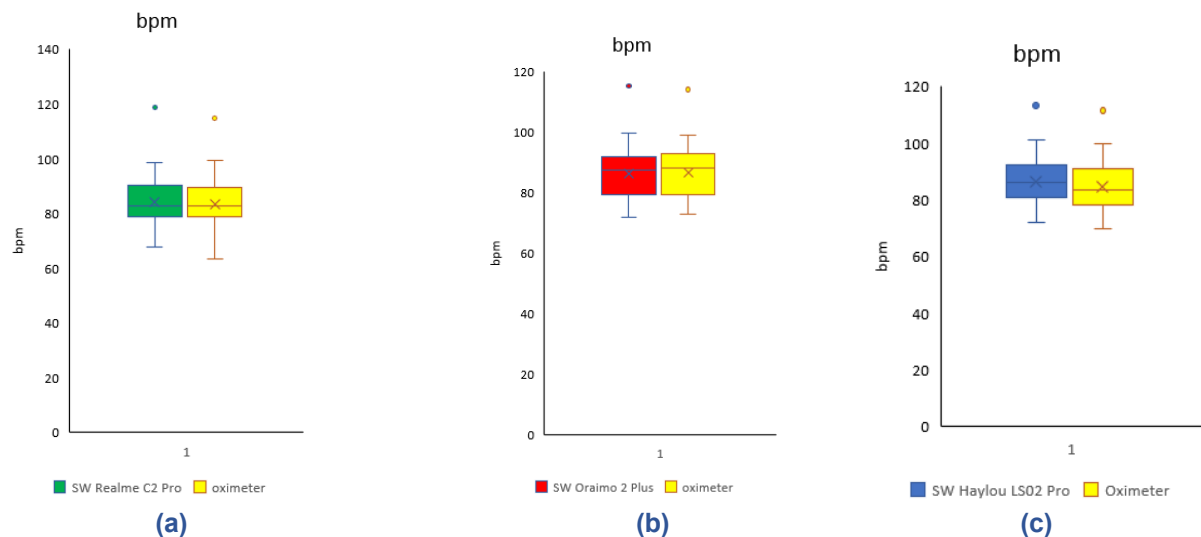


Fig. 5. Comparison of smartwatches and oximeter of heart rate: (a) Realme C2 Pro, (b) Oramo 2 Plus, and (c) Haylou LS02 Pro

The mean differences across the devices, smartwatches tend to show higher SpO2 readings than conventional oximeters as shown in Figure 4 & Figure 5 below. Haylou

SW tend to shows the biggest difference with the oximeter compared to other smartwatches, yet it remains within normal ranges

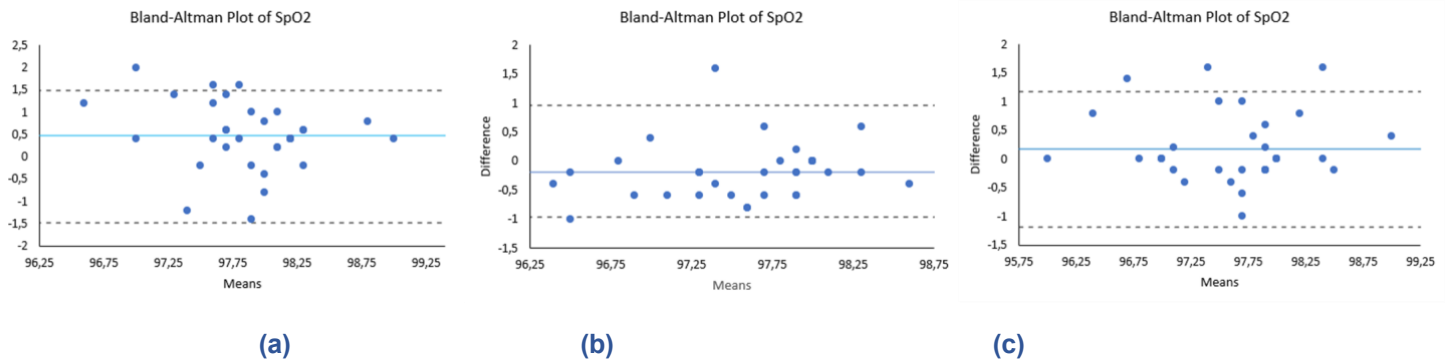


Fig. 6. Bland-Altman plot of SpO₂ on smartwatches: (a) Realme C2 Pro, (b) Oramo 2 Plus OSW- 32N and (c) Haylou LS02 Pro. (Solid lines show the mean bias & dashed line represents upper and lower limits of agreement)

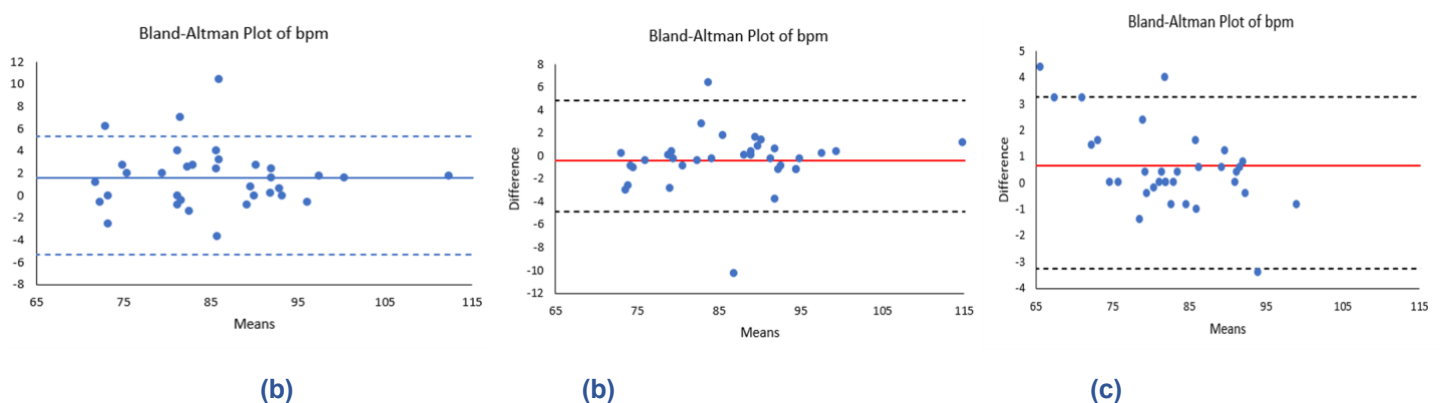


Fig. 7. Bland-Altman plot of bpm on smartwatches: (a) Realme C2 Pro, (b) Oramo 2 Plus OSW- 32N and (c) Haylou LS02 Pro. (Solid lines show the mean bias & dashed line represents upper and lower limits of agreement)

Bland-Altman plots were used to assess the level of agreement between SpO₂ and bpm readings obtained from smartwatches and a standard oximeter. Figure 6(a) presents the Bland-Altman plot for the Realme C2 Pro smartwatch, indicating a bias of 0.48 in SpO₂ measurements, with limits of agreement ranging from -1.4794 to 1.4794. For the Oramo 2 Plus, the measurement bias was -0.19, while the Haylou LS02 Pro showed a bias of 0.18. As illustrated in Figures 5b and 5c, the limits of agreement for the Oramo 2 Plus and Haylou LS02 Pro were between -0.959 to 0.9599% and -1.1849 to 1.1849, respectively as shown in Figure 6 (b) and (c). Figure 7 depicts Bland-Altman plot of bpm readings from smartwatches and commercial oximeters. The bias and LoA across the device were found at 1.57 and -5.3043 to 5.3043 for Realme C2 Pro (Fig. 7a), -0.38% and -4.8797 to 4.8797 for Oramo 2 Plus (Fig. 7b) and 0.6 and -3.2556 to 3.2556 for Haylou LS02 pro (Fig. 7c).

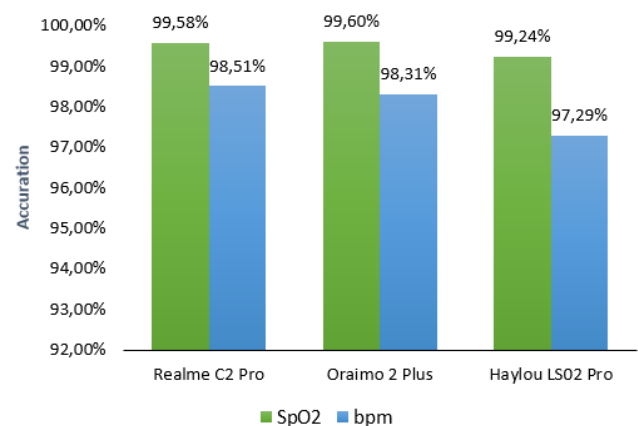


Fig. 8. The accuracy of SpO₂ & bpm on smartwatches

Figure 8 illustrates the measurement accuracy of SpO₂ and bpm across the three smartwatches. Overall, the Realme smartwatch demonstrated the highest accuracy, achieving 99.58% for SpO₂ and 98.515% for bpm. In contrast, the Haylou smartwatch recorded the lowest accuracy, with values of 99.24% for SpO₂ and 97.29% for bpm.

4. DISCUSSION

The findings from this study indicate that commercially available smartwatches, particularly the Realme C2 Pro, are capable of producing accurate measurements of blood oxygen saturation and heart rate when compared to a standard medical-grade oximeter. The Realme C2 Pro consistently demonstrated the smallest measurement bias and the narrowest limits of agreement in Bland-Altman analyses, suggesting a high level of reliability. This performance is likely influenced by superior sensor integration and signal processing algorithms, which are critical for PPG-based measurements as stated in research carried by Chan et al. in 2013. Despite using similar PPG technology, the measurement accuracy of the Oramo 2 Plus and Haylou LS02 Pro was slightly lower. The Haylou smartwatch, in particular, showed the highest variability and lowest accuracy in both SpO₂ and bpm values. These discrepancies can be attributed to differences in sensor quality, device calibration, and the proprietary algorithms used by each manufacturer. Prior studies have similarly reported significant variation in accuracy across different smartwatch models, with error rates occasionally exceeding 5% in line with the research conducted by Boudreaux et al. in 2020, a level that could potentially impact clinical decision-making.

Across all devices tested, we observed a consistent tendency for the smartwatches to slightly overestimate both SpO₂ and BPM readings compared to the reference device. Although this bias remained within acceptable limits, it is important to consider its potential impact on clinical interpretation, especially in cases where precise monitoring is critical. In self-monitoring contexts, this overestimation could delay timely clinical intervention or create false reassurance. Future studies should explore whether correction algorithms or calibration adjustments can help minimize this bias. Another notable factor is the influence of user-specific variables such as skin tone, movement, and positioning of the smartwatch during measurements. Our sample included a diverse range of skin tones based on the Fitzpatrick scale, which may affect light absorption and thus the accuracy of PPG signals. Previous research has noted that darker skin tones can lead to reduced accuracy in optical sensors due to increased melanin absorption, as stated in Weinrauch & Rauchenzauner's research in 2021. While the current study did not stratify accuracy by skin tone, future investigations should consider this variable for a more comprehensive analysis. Moreover, other influencing factors such as wrist positioning, user movement, hydration level, and lighting conditions were partially controlled. Participants were instructed to remain still, seated in a well-lit environment with neutral temperature. However, hydration level and long-term testing across multiple sessions were not addressed and represent limitations in our experimental control. Addressing these physiological and environmental factors is critical for producing robust validation in future research.

Furthermore, while correlation coefficients between smartwatch and oximeter readings were generally high,

correlation alone is not sufficient to determine agreement. The use of Bland-Altman analysis in this study addressed this gap by evaluating the degree of bias and variability between devices. Our findings confirm that although smartwatches can track trends reliably, slight biases remain. Nonetheless, the observed accuracy levels suggest that these devices are acceptable for non-clinical, self-monitoring purposes, especially in younger populations.

This study reinforces the potential of smartwatches as practical tools for personal health monitoring. While they are not yet replacements for clinical devices, smartwatches may serve as early warning systems for health abnormalities, prompting users to seek medical advice. With continued technological improvements and algorithm optimization, wearable devices may play an increasingly significant role in preventive healthcare and remote patient monitoring, aligning with the broader goals of digital medicine. This is supported by research conducted by Bent et al. in 2020. Nevertheless, the scope of this study was limited to only three smartwatch models and a cross-sectional testing design. Future research should expand the number of devices evaluated and include longitudinal studies to assess consistency over time and under firmware/software updates, which can influence measurement performance.

5. CONCLUSION

This study successfully assessed the accuracy of key health-tracking features i.e. blood oxygen and heart rate, on commercially available smartwatches. Among the devices tested, the Realme C2 Pro outperformed the others, achieving the accuracy at 99.58% for SpO₂ and 98.515% for heart rate. The Oramo 2 Plus also showed strong performance (99.60% for SpO₂ and 98.31% for bpm), and the Haylou LS02 Pro, while slightly less accurate (99.24% for SpO₂ and 97.29% for bpm), remained within acceptable limits. All devices demonstrated potential as non-clinical health monitoring tools. Minor positive biases were observed, with smartwatch readings tending to slightly overestimate values. While this does not significantly affect general usage, it highlights the need for cautious interpretation in clinical contexts. This study supports the role of smartwatches as accessible tools for early detection and continuous health tracking. Future work should include longitudinal testing, broader device representation, and subgroup analyses based on skin tone and user-specific factors to further validate performance.

REFERENCES

- [1] P. P. Ray, D. Dash, and N. Kumar, "Sensors for internet of medical things: State-of-the-art, security and privacy issues, challenges and future directions," *Comput. Commun.*, vol. 160, no. April, pp. 111–131, 2020, doi: 10.1016/j.comcom.2020.05.029.
- [2] Y. Jiang, C. Spies, J. Magin, S. J. Bhosai, L. Snyder, and J. Dunn, "Investigating the accuracy of

- blood oxygen saturation measurements in common consumer smartwatches," *PLOS Digit. Heal.*, vol. 2, no. 7, p. e0000296, 2023, doi: 10.1371/journal.pdig.0000296.
- [3] Y. Lu, Z. Zhou, and X. Li, "Study on the relationship between technology, data and body isomorphism—The example of smartwatches," *Telemat. Informatics Reports*, vol. 13, no. April 2023, p. 100118, 2024, doi: 10.1016/j.teler.2024.100118.
- [4] S. Chakrabarti, N. Biswas, L. D. Jones, S. Kesari, and S. Ashili, "Smart Consumer Wearables as Digital Diagnostic Tools: A Review," *Diagnostics*, vol. 12, no. 9, pp. 1–19, 2022, doi: 10.3390/diagnostics12092110.
- [5] C. Köhler, A. Bartschke, D. Fürstenau, T. Schaaf, and E. Salgado-Baez, "The value of smartwatches in the healthcare sector: Monitoring, nudging, and predicting (Preprint)," *J. Med. Internet Res.*, no. October, 2024, doi: 10.2196/58936.
- [6] M. Masoumian Hosseini, S. T. Masoumian Hosseini, K. Qayumi, S. Hosseinzadeh, and S. S. Sajadi Tabar, "Smartwatches in healthcare medicine: assistance and monitoring; a scoping review," *BMC Med. Inform. Decis. Mak.*, vol. 23, no. 1, pp. 1–26, 2023, doi: 10.1186/s12911-023-02350-w.
- [7] K. J. Bin, L. R. De Pretto, F. B. Sanchez, and L. R. Battistella, "Digital Platform to Continuously Monitor Patients Using a Smartwatch: Preliminary Report," *JMIR Form. Res.*, vol. 6, no. 9, pp. 1–12, 2022, doi: 10.2196/40468.
- [8] B. Bent, B. A. Goldstein, W. A. Kibbe, and J. P. Dunn, "Investigating sources of inaccuracy in wearable optical heart rate sensors," *npj Digit. Med.*, vol. 3, no. 1, pp. 1–9, 2020, doi: 10.1038/s41746-020-0226-6.
- [9] P. Windisch, C. Schröder, R. Förster, N. Cihoric, and D. R. Zwahlen, "Accuracy of the Apple Watch Oxygen Saturation Measurement in Adults: A Systematic Review," *Cureus*, vol. 15, no. 2, 2023, doi: 10.7759/cureus.35355.
- [10] A. Moço and W. Verkruysse, "Pulse oximetry based on photoplethysmography imaging with red and green light: Calibratability and challenges," *J. Clin. Monit. Comput.*, vol. 35, no. 1, pp. 123–133, 2021, doi: 10.1007/s10877-019-00449-y.
- [11] J. Park, H. S. Seok, S. S. Kim, and H. Shin, "Photoplethysmogram Analysis and Applications: An Integrative Review," *Front. Physiol.*, vol. 12, no. March, pp. 1–23, 2022, doi: 10.3389/fphys.2021.808451.
- [12] S. Zhu, S. Liu, X. Jing, Y. Yang, and C. She, "Innovative approaches in imaging photoplethysmography for remote blood oxygen monitoring," *Sci. Rep.*, vol. 14, no. 1, pp. 1–13, 2024, doi: 10.1038/s41598-024-70192-1.
- [13] A. M. Cabanas *et al.*, "Evaluating AI Methods for Pulse Oximetry: Performance, Clinical Accuracy, and Comprehensive Bias Analysis," *Bioengineering*, vol. 11, no. 11, pp. 1–26, 2024, doi: 10.3390/bioengineering11111061.
- [14] T. Tamura, "Current progress of photoplethysmography and SPO2 for health monitoring," *Biomed. Eng. Lett.*, vol. 9, no. 1, pp. 21–36, 2019, doi: 10.1007/s13534-019-00097-w.
- [15] T. Y. Abay and P. A. Kyriacou, "Photoplethysmography for blood volumes and oxygenation changes during intermittent vascular occlusions," *J. Clin. Monit. Comput.*, vol. 32, no. 3, pp. 447–455, 2018, doi: 10.1007/s10877-017-0030-2.
- [16] M. A. Almarshad, M. S. Islam, S. Al-Ahmadi, and A. S. Bahammam, "Diagnostic Features and Potential Applications of PPG Signal in Healthcare: A Systematic Review," *Healthc.*, vol. 10, no. 3, pp. 1–28, 2022, doi: 10.3390/healthcare10030547.
- [17] G. of Canada, "Pulse Oximeters: For Consumers," 2022. <https://www.canada.ca/en/health-canada/services/drugs-medical-devices/pulse-oximeters/consumers.html> (accessed May 18, 2025).
- [18] T. Dünwald, R. Kienast, D. Niederseer, and M. Burtcher, "The use of pulse oximetry in the assessment of acclimatization to high altitude," *Sensors (Switzerland)*, vol. 21, no. 4, pp. 1–20, 2021, doi: 10.3390/s21041263.
- [19] M. Shafique, P. A. Kyriacou, and S. K. Pal, "Investigation of photoplethysmographic signals and blood oxygen saturation values on healthy volunteers during cuff-induced hypoperfusion using a multimode PPG/SpO₂ sensor," *Med. Biol. Eng. Comput.*, vol. 50, no. 6, pp. 575–583, 2012, doi: 10.1007/s11517-012-0910-z.
- [20] K. Paluch *et al.*, "Accuracy of Wrist-Worn Heart Rate Monitors: A Comprehensive Review of Smartwatches in Exercise Monitoring," pp. 1–31, 2024.
- [21] K. B. Kim and H. J. Baek, "Photoplethysmography in Wearable Devices: A Comprehensive Review of Technological Advances, Current Challenges, and Future Directions," *Electron.*, vol. 12, no. 13, 2023, doi: 10.3390/electronics12132923.
- [22] C. Spaccarotella, A. Polimeni, C. Mancuso, G. Pelaia, G. Esposito, and C. Indolfi, "Assessment of Non-Invasive Measurements of Oxygen Saturation and Heart Rate with an Apple Smartwatch: Comparison with a Standard Pulse Oximeter," *J. Clin. Med.*, vol. 11, no. 6, pp. 0–6, 2022, doi: 10.3390/jcm11061467.
- [23] S. Walzel, R. Mikus, V. Rafl-huttova, M. Rozanek, T. E. Bachman, and J. Rafl, "Evaluation of Leading Smartwatches for the Detection of Hypoxemia: Comparison to Reference Oximeter," *Sensors*, vol. 23, pp. 1–12, 2023, doi: <https://doi.org/10.3390/s23229164>.
- [24] S. H. Browne, M. Bernstein, and P. E. Bickler,

- "Evaluation of Pulse Oximetry Accuracy in a Commercial Smartphone and Smartwatch Device During Human Hypoxia Laboratory Testing," *Sensors*, vol. 25, no. 5, pp. 1–16, 2025, doi: 10.3390/s25051286.
- [25] K. Rajakariar *et al.*, "Accuracy of Smartwatch Pulse Oximetry Measurements in Hospitalized Patients With Coronavirus Disease 2019," *Mayo Clin. Proc. Digit. Heal.*, vol. 2, no. 1, pp. 152–158, 2024, doi: 10.1016/j.mcpdig.2024.02.001.
- [26] R.-H. V. W. S. R. M. Rafi J Bachman TE, "Commercial smartwatch with pulse oximeter detects short-time hypoxemia as well as standard medical-grade device: Validation study.,", 2022, doi: 10.1177/20552076221132127.
- [27] A. Hughes, M. M. H. Shandhi, H. Master, J. Dunn, and E. Brittain, "Wearable Devices in Cardiovascular Medicine," *Circ. Res.*, vol. 132, no. 5, pp. 652–670, 2023, doi: 10.1161/CIRCRESAHA.122.322389.
- [28] E. A. Jafleh, F. A. Alnaqbi, H. A. Almaeeni, S. Fageeh, M. A. Alzaabi, and K. Al Zaman, "The Role of Wearable Devices in Chronic Disease Monitoring and Patient Care: A Comprehensive Review," *Cureus*, vol. 16, no. 9, 2024, doi: 10.7759/cureus.68921.
- [29] A. Shcherbina *et al.*, "Accuracy in wrist-worn, sensor-based measurements of heart rate and energy expenditure in a diverse cohort," *J. Pers. Med.*, vol. 7, no. 2, pp. 1–12, 2017, doi: 10.3390/jpm7020003.
- [30] L. Z. Pipek, R. F. V. Nascimento, M. M. P. Acencio, and L. R. Teixeira, "Comparison of SpO2 and heart rate values on Apple Watch and conventional commercial oximeters devices in patients with lung disease," *Sci. Rep.*, vol. 11, no. 1, pp. 1–7, 2021, doi: 10.1038/s41598-021-98453-3.
- [31] A. Totuk, B. Bayramoglu, and I. Tayfur, "Reliability of smartphone measurements of peripheral oxygen saturation and heart rate in hypotensive patients measurement of vital signs with smartphones," *Heliyon*, vol. 9, no. 2, p. e13145, 2023, doi: 10.1016/j.heliyon.2023.e13145.
- [32] A. B. Shrestha *et al.*, "Navigating the Role of Smartwatches in Cardiac Fitness Monitoring: Insights from Physicians and the Evolving Landscape," *Curr. Probl. Cardiol.*, vol. 49, no. 1, p. 102073, 2023, doi: 10.1016/j.cpcardiol.2023.102073.
- [33] B. W. Nelson and N. B. Allen, "Accuracy of consumer wearable heart rate measurement during an ecologically valid 24-hour period: Intraindividual validation study," *JMIR mHealth uHealth*, vol. 7, no. 3, pp. 1–16, 2019, doi: 10.2196/10828.
- [34] K. Angeloudis, B. Muniz-pardos, R. Gregory, and R. A. Huggins, "Establishing a Global Standard for Wearable Devices in Sport and Exercise Medicine: Perspectives from Academic and Industry Stakeholders," vol. 51, no. 11, pp. 2237–2250, 2022, doi: 10.1007/s40279-021-01543-5. Establishing.
- [35] R. Argent *et al.*, "Recommendations for Determining the Validity of Consumer Wearables and Smartphones for the Estimation of Energy Expenditure: Expert Statement and Checklist of the INTERLIVE Network," *Sport. Med.*, vol. 52, no. 8, pp. 1817–1832, 2022, doi: 10.1007/s40279-022-01665-4.
- [36] W. Johnston *et al.*, "Recommendations for determining the validity of consumer wearable and smartphone step count: Expert statement and checklist of the INTERLIVE network," *Br. J. Sports Med.*, vol. 55, no. 14, pp. 780–793, 2021, doi: 10.1136/bjsports-2020-103147.
- [37] R. S. Thiebaud *et al.*, "Validity of wrist-worn consumer products to measure heart rate and energy expenditure," *Digit. Heal.*, vol. 4, p. 205520761877032, 2018, doi: 10.1177/2055207618770322.
- [38] C. Doherty, M. Baldwin, A. Keogh, B. Caulfield, and R. Argent, "Keeping Pace with Wearables: A Living Umbrella Review of Systematic Reviews Evaluating the Accuracy of Consumer Wearable Technologies in Health Measurement," *Sport. Med.*, vol. 54, no. 11, pp. 2907–2926, 2024, doi: 10.1007/s40279-024-02077-2.
- [39] N. Sharma *et al.*, "A smart ontology-based IoT framework for remote patient monitoring," *Biomed. Signal Process. Control*, vol. 68, no. May, p. 102717, 2021, doi: 10.1016/j.bspc.2021.102717.
- [40] I. Shapiro, J. Stein, C. MacRae, and M. O'Reilly, "Pulse oximetry values from 33,080 participants in the Apple Heart & Movement Study," *npj Digit. Med.*, vol. 6, no. 1, pp. 0–34, 2023, doi: 10.1038/s41746-023-00851-6.
- [41] D. Giavarina, "Understanding Bland Altman analysis," *Biochem. Medica*, vol. 25, no. 2, pp. 141–151, 2015, doi: 10.11613/BM.2015.015.
- [42] P. Taffé, "When can the Bland & Altman limits of agreement method be used and when it should not be used," *J. Clin. Epidemiol.*, vol. 137, pp. 176–181, 2021, doi: 10.1016/j.jclinepi.2021.04.004.

AUTHOR BIOGRAPHY



Kusnanto Mukti Wibowo was born in Sukoharjo, Indonesia on December 18, 1991. He received Bachelor of Science degree from Sebelas Maret University, Indonesia in 2013. In 2018, he obtained his Master of Engineering (M.Eng.) from University Tun Hussein Onn Malaysia (UTHM), Johor, Malaysia. He started working as Lecturer at Department of Medical Electronic Engineering Technology, Faculty of Health Science, University of

Muhammadiyah Purwokerto (UMP) in 2020. His research interests include sensor, biosensor and diagnostic.



Royan is a lecturer at department of Medical Electronic Engineering Technology, Faculty of Health Science, University of Muhammadiyah Purwokerto (UMP). He was born in Semarang in December 1987. He earned a Master degree in Electrical Engineering from Diponegoro University. He has also worked as a professional electromedical engineer in a hospital for 8 years. He is now actively conducting research in the field of electromedical engineering.



Abdul Latif was born in Banyumas, Central Java, Indonesia. He obtained the title of Associate Expert in Electrical Engineering at the Muhammadiyah Polytechnic of Yogyakarta in 2013. He received a Bachelor of Engineering degree from Respati University Yogyakarta, Indonesia in 2017, and M.Eng. degree in Electrical Engineering from Universitas Islam Sultan Agung, Semarang, Indonesia in 2021. He started working as Lecturer at Department of Medical Electronic Engineering Technology, Faculty of Health Science, University of Muhammadiyah Purwokerto (UMP) in 2023. His interests research includes medical devices, IoT, and robotics.



Fani Susanto was born in Banyumas, Central Java, Indonesia. He obtained the title of Associate Expert in Electrical Engineering at the Muhammadiyah Polytechnic of Yogyakarta in 2013. He received a Bachelor of Engineering degree from Respati University Yogyakarta, Indonesia in 2017 and M.Eng. degree in Electrical Engineering from Universitas Islam Sultan Agung, Semarang, Indonesia in 2021. He started working as

Lecturer at Department of Medical Electronic Engineering Technology, Faculty of Health Science, University of Muhammadiyah Purwokerto (UMP) in 2023. His interests research includes medical devices, IoT, and robotics.

Fatiatun received her bachelor's degree in physics (materials) from Semarang State University (UNNES), Indonesia in 2015, her Master of Science (M.Sc) in materials physics from Sultan Idris Education University (UPSI), Malaysia in 2018, and is currently pursuing her Doctor of Philosophy (PhD) in materials physics at Sultan Idris Education University (UPSI), Malaysia. Since 2016, she has joined the Nano Research Centre (NRC) at UPSI. From 2019 to the present, she has been a lecturer in Physics Education at Al-Qur'an Science University (UNSIQ).



Norhidayah Che Ani received her Bachelor's degree in Electrical Engineering from Universiti Tun Hussein Onn Malaysia (UTHM) in 2012. She also holds a Master's degree in Electrical Engineering from the same university. She is currently pursuing a Ph.D. in Electrical Engineering at UTHM. In addition to her academic pursuits, she has ventured into freelance work as a formatter and editor.



Rudi Irmawanto was born in Lamongan, Indonesia on June 09, 1984. He received Bachelor of Electrical Engineering degree from University of Muhammadiyah Surabaya, Indonesia in 2007. He obtained his Master of Engineering (M.Eng.) from Universitas Islam Sultan Agung, Semarang, Indonesia in 2019. He started working as Lecturer in Department of Electrical Engineering, University of Muhammadiyah Surabaya in 2020.

Each author is required to provide a cover image as shown example below

