

## Technical Brief

## A Low Cost Real Time ECG and PPG System for Orthopedic Rehabilitation and Mobilization Tracking: A Technical Note

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## ARTICLE INFO

## Article history:

Submitted September 3

Accepted September 16

Publication September 30

## Keywords:

Electrocardiography

Photoplethysmography

Arduino

Biomedical Signal Processing

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0009-0002-6061-0612

## ABSTRACT

**Objective:** To develop an end to end, low cost system that simultaneously acquires electrocardiogram (ECG) and photoplethysmogram (PPG) signals, computes heart rate (HR), heart rate variability (HRV) metrics (SDNN, RMSSD), and peripheral oxygen saturation (SpO<sub>2</sub>), and enables direct comparison of electrical versus optical methods while generating a custom dataset.

**Methods:** An Arduino Nano Matter microcontroller was interfaced with a DFRobot SEN0213 ECG module (three electrode configuration) and a MAX30102 PPG/SpO<sub>2</sub> sensor. Raw signals were streamed via serial communication to a host computer. A custom software pipeline performed preprocessing, peak detection (R peaks for ECG, pulse peaks for PPG), calculation of HR/SDNN/RMSSD/SpO<sub>2</sub>, real time dashboard visualization, and session based data logging to build a personal dataset.

**Results:** In a representative 10 minute resting recording, mean HR was identical between methods (96 BPM for both ECG and PPG). SDNN values were closely matched (107 ms ECG vs 109 ms PPG), while RMSSD showed a modest difference (170 ms ECG vs 192 ms PPG). Mean SpO<sub>2</sub> was 95%. Short recordings exhibited larger transient HR discrepancies that diminished with longer acquisition duration.

**Conclusion:** The system successfully demonstrates simultaneous dual modality acquisition and comparative analysis of ECG and PPG derived cardiac parameters. It provides a practical educational and prototyping platform for biomedical signal processing and digital health applications. The device is not intended for clinical diagnosis

## Doi:

<https://doi.org/10.5281/zenodo.22831273>

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## Introduction

Heart rate (HR) and heart rate variability (HRV) are fundamental physiological parameters that reflect both cardiac function and autonomic nervous system activity (Shaffer & Ginsberg, 2017; Malik et al., 1996). HRV, in particular, has emerged as a sensitive non invasive marker of autonomic balance, with applications ranging from cardiovascular risk stratification and stress assessment to athletic recovery monitoring and digital health interventions (Shaffer & Ginsberg, 2017; Malik et al., 1996). Accurate quantification of these metrics remains essential in both clinical practice and wearable technology development.

Electrocardiography (ECG) continues to serve as the clinical gold standard for HR and HRV analysis because it directly records the electrical activity of the heart and allows precise identification of R R intervals (Malik et al., 1996). In contrast, photoplethysmography (PPG) estimates cardiac timing indirectly by detecting volumetric changes in peripheral blood flow (Allen, 2007). Owing to its convenience convenience, low cost, and ability to simultaneously estimate peripheral oxygen saturation (SpO<sub>2</sub>), PPG has become the dominant sensing modality in consumer wearables and continuous monitoring systems (Allen, 2007).

Despite advances in arthroscopic fixation techniques, biological healing remains a major limitation of meniscal repair. Classic anatomical investigations demonstrated that only the peripheral portion of the adult human meniscus receives penetrating vascular supply (Arnoczky & Warren, 1982; Arnoczky & Warren, 1983). Consequently, tears involving relatively avascular regions have less intrinsic healing potential, and successful repair depends not only on mechanical fixation but also on the local biological environment (Makris et al., 2011; Vaquero & Forriol, 2016).

Despite their widespread use, ECG derived HRV and PPG derived pulse rate variability (PRV) are not physiologically equivalent. The temporal delay between the electrical R peak and the arrival of the peripheral pulse wave known as pulse arrival time (PAT) or pulse transit time (PTT) introduces additional variability that is modulated by vascular tone, blood pressure, respiration, and autonomic state (Dewig et al., 2024). Consequently, successive pulse to pulse intervals differ from the corresponding R R intervals, particularly affecting high frequency metrics such as the root mean square of successive differences (RMSSD).

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**Cite this article:** Türkoğlu, İ., & Deveci, A. (2026). A low cost real time ECG and PPG system for orthopedic rehabilitation and mobilization tracking: A technical note. *Journal of Baltalimani*, 2(3), 81–85.

Large scale clinical and athletic studies published in 2025 and 2026 have confirmed statistically significant disagreements between PRV and HRV across multiple time domain indices, leading to the clear recommendation that PRV should not be treated as a direct surrogate for HRV (Kantrowitz et al., 2025; Ben David et al., 2026). Under resting conditions and with sufficient recording duration, however, mean heart rate and certain global measures such as the standard deviation of NN intervals (SDNN) can show closer agreement (Coste et al., 2025).

Understanding these modality specific differences is particularly relevant for biomedical engineering education, algorithm development, and the design of multimodal wearable systems. Yet most existing comparative studies rely on commercial grade or clinical equipment, limiting accessibility for teaching laboratories and low resource research environments. In the specific context of orthopedics and musculoskeletal care, tracking autonomic load, physiological stress, and cardiac response during post operative mobilization and early physical rehabilitation sessions is increasingly recognized as potentially valuable. However, the bulkiness and high cost of traditional clinical monitoring equipment hinder continuous bedside or field level assessment. There remains a practical need for an end to end, low cost platform capable of simultaneously acquiring single lead ECG and PPG signals, computing key cardiac and oxygenation parameters in real time, visualizing the results, and systematically logging data for dataset construction.

The present technical note addresses this gap by describing a complete, Arduino based system that integrates a three electrode ECG module with a MAX30102 PPG/SpO<sub>2</sub> sensor. The system performs continuous dual modality acquisition, real time peak detection, calculation of HR, SDNN, RMSSD and SpO<sub>2</sub>, live dashboard visualization, and session based data logging. By enabling direct side by side comparison of electrical and optical cardiac metrics under controlled conditions, the platform serves both as an educational tool for illustrating the physiological and technical differences between ECG and PPG and as a flexible prototyping environment. While the current evaluation was limited to a single healthy subject under resting conditions, the system is conceptually positioned to support future investigations of physiological monitoring during orthopedic rehabilitation and mobilization protocols.

## Materials and methods

### Hardware Architecture

The system was built around an Arduino Nano Matter (ABX00112) microcontroller board. Two sensors were connected via a breadboard:

DFRobot SEN0213 ECG sensor module acquires the cardiac electrical signal through three disposable electrodes (right arm, left arm, and right leg drive/ground) and provides an analog output. MAX30102 integrated pulse oximeter and heart rate sensor contains red and infrared LEDs plus a photodetector for PPG waveform acquisition and SpO<sub>2</sub> estimation.

Both sensors shared power and data lines on the breadboard and were continuously sampled at a uniform sampling frequency of 100 Hz within the Arduino main loop. Timestamped raw data were transmitted via USB serial communication to a host computer. Although acquisition was performed in the same main loop, minor microcontroller timing jitters between the independent analog channel (ECG read via ADC) and digital channel (PPG read via I<sup>2</sup>C) are acknowledged as an inherent hardware level synchronization limitation. This jitter can influence precise beat to beat (RR versus PP) interval comparisons.

### Software Pipeline

A six stage processing chain was implemented in Python:

Simultaneous continuous sampling: Dual channel acquisition of analog ECG and digital PPG signals at a uniform sampling frequency of 100 Hz. Preprocessing and filtering: For the ECG channel, a 2nd order Butterworth bandpass filter (0.5 40 Hz) with stateful filtering (lfilter\_zi) was applied to eliminate baseline wander and high frequency noise. For the PPG channel, a 30 sample moving average filter was used to extract and remove the DC component, thereby isolating the AC pulsatile signal. Peak detection and signal quality control: ECG R wave peaks and PPG systolic pulse peaks were identified using `scipy.signal.find_peaks` with a minimum inter peak distance of 0.4 s (corresponding to a maximum heart rate of 150 BPM). No additional prominence or height threshold was applied beyond the distance constraint in order to maintain sensitivity. A simple Signal Quality Index (SQI) based on kurtosis (`scipy.stats.kurtosis`) and peak to peak amplitude was calculated for each sliding window; segments falling outside empirically defined acceptable ranges were flagged as potential motion or contact artefacts. Flagged segments were excluded from final HRV metric calculation.

Parameter calculation: RR (or peak to peak) intervals, instantaneous and mean heart rate (HR), standard deviation of NN intervals (SDNN), and root mean square of successive differences (RMSSD) were computed for each modality across short (~30 s) and extended (~10 min) resting sessions.

Empirical SpO<sub>2</sub> estimation: Peripheral oxygen saturation (SpO<sub>2</sub>) was estimated from the ratio of red to infrared light absorption using the standard AC/DC form:

$$R = \frac{(AC_{red}/DC_{red})}{(AC_{IR}/DC_{IR})}$$

followed by an empirical linear approximation commonly used with the MAX30102. The resulting value represents an uncalibrated relative optical estimate and was not validated against a reference pulse oximeter.

Real time visualization and logging: Live dashboard rendering and session based logging of raw signals plus derived physiological metrics into structured CSV files.

### Data Collection Protocol

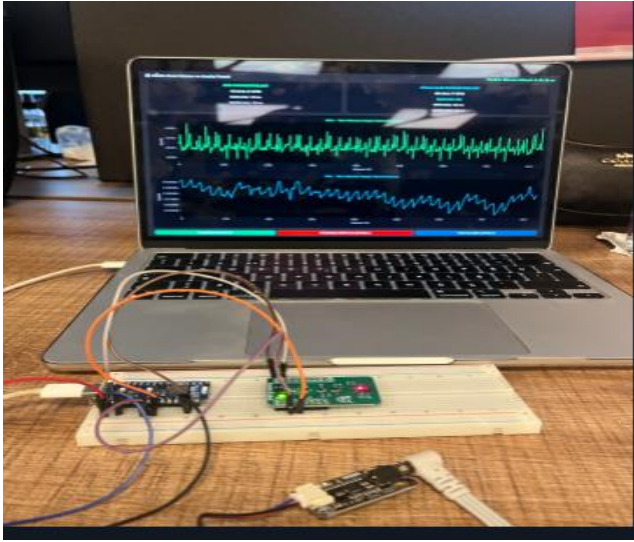
Measurements were performed on a single healthy adult subject (the author) under resting conditions in a seated position. Each recording was managed as a discrete session that could be started, stopped, and saved. Both short (~30 s) and longer (~10 min) sessions were acquired. The dashboard displayed live waveforms, instantaneous parameter cards (HR, SDNN, RMSSD for ECG and PPG, plus SpO<sub>2</sub>), and session duration. At the end of each session the computed averages were stored. For visual reference, a clinical grade patient monitor (Philips IntelliVue MX550) was available in the same environment and was used to observe concurrent HR and SpO<sub>2</sub> values; however, quantitative simultaneous data export from the clinical monitor was not performed in the present technical demonstration.

## Results

A clinical grade Philips IntelliVue MX550 monitor was present in the recording environment and provided visual confirmation of heart rate and SpO<sub>2</sub> values in the same range as those obtained by the low cost system, although formal simultaneous quantitative comparison was beyond the scope of this technical feasibility study

The complete experimental setup is shown in Figure 1. The Arduino Nano Matter microcontroller, DFRobot SEN0213 ECG module and MAX30102 PPG/SpO<sub>2</sub> sensor were assembled on a breadboard and connected to a host computer via USB serial communication. Real time dual modality acquisition, peak detection, parameter calculation and visualisation were performed by the custom software pipeline described in the Methods section.

**Figure 1.** Experimental hardware setup of the dual modality system. The Arduino Nano Matter board, DFRobot SEN0213 ECG module and MAX30102 sensor are mounted on a breadboard and interfaced with a laptop running the real time analysis software.



For visual reference comparison, a clinical grade patient monitor (Philips IntelliVue MX550) was available in the same environment during data collection (Figure 2). The monitor displayed heart rate and SpO<sub>2</sub> values in a similar range to those obtained by the low cost system; however, simultaneous quantitative data export and formal agreement analysis were not performed in this technical demonstration.

**Figure 2.** Clinical grade reference monitor (Philips IntelliVue MX550) present in the recording environment, showing concurrent heart rate and SpO<sub>2</sub> values for visual comparison.



**Figure 3.** Real time clinical monitoring and analysis dashboard after a 10 min 2 s resting session. The upper panels show mean HR, SDNN and RMSSD for ECG (left) and PPG + SpO<sub>2</sub> (right). The lower panels display the complete ECG (green) and PPG (blue) waveforms recorded during the entire session.



A representative 10 minute 2 second resting recording was analysed in detail. The corresponding real time monitoring dashboard is presented in Figure 3. Mean heart rate was identical between the two modalities (96 BPM for both ECG and PPG). SDNN values were closely matched (107 ms ECG vs 109 ms PPG), while RMSSD showed a modest difference (170 ms ECG vs 192 ms PPG). Mean SpO<sub>2</sub> was 95%. These summary statistics are listed in Table 1.

**Table 1.** Comparison of ECG and PPG derived parameters (10 min 2 s resting session)

| Parameter       | ECG (Electrical) | PPG (Optical) |
|-----------------|------------------|---------------|
| Mean HR (BPM)   | 96               | 96            |
| Mean SDNN (ms)  | 107              | 109           |
| Mean RMSSD (ms) | 170              | 192           |
| Mean SpO2 (%)   |                  | 95            |

In a short (~32 s) session the instantaneous heart rate values diverged more noticeably (ECG 91 BPM vs PPG 77 BPM). Extending the recording to approximately 10 minutes eliminated the mean HR difference and produced closely aligned SDNN values, illustrating the benefit of longer acquisition windows for stable comparison. The full session ECG and PPG waveforms displayed on the dashboard (Figure 3) further confirm that both signals remained continuous and of sufficient quality for peak detection throughout the 10 minute recording. The relatively high RMSSD values observed in both modalities (170 ms ECG vs 192 ms PPG) and the larger discrepancies seen in short recordings are noted and will be examined in the Discussion in relation to possible residual artefacts, contact quality, and the inherent limitations of the hardware synchronization.

## Discussion

The simultaneous acquisition of single lead ECG and PPG signals in the present system revealed both expected concordance and characteristic divergences between the two modalities. In the representative 10 minute resting recording, mean heart rate was identical (96 BPM), and SDNN values were nearly equivalent (107 ms versus 109 ms). In contrast, RMSSD was modestly higher when derived from the PPG channel (192 ms versus 170 ms). Short (~30 s) recordings produced larger instantaneous discrepancies that largely disappeared with longer acquisition windows,

underscoring the importance of sufficient recording duration for stable comparative statistics.

These findings are consistent with a growing body of evidence demonstrating that pulse rate variability (PRV) extracted from PPG is not interchangeable with true heart rate variability (HRV) obtained from ECG. Large scale clinical investigations have shown statistically significant disagreement between the two approaches across multiple time domain metrics, with PRV frequently under or over estimating SDNN, RMSSD and pNN50 depending on the population and recording conditions (Kantrowitz et al., 2025; Ben David et al., 2026). The principal physiological source of this discrepancy is the pulse arrival time (PAT) or pulse transit time (PTT) the interval between the electrical R peak and the arrival of the pressure wave at the peripheral measurement site. Because PAT itself varies with respiration, vascular tone and autonomic state, successive pulse to pulse intervals are not simply delayed versions of the corresponding R R intervals; the variability introduced by oscillating PAT is inherently greater for high frequency metrics such as RMSSD than for SDNN (Dewig et al., 2024). Technical factors further amplify these differences. PPG waveforms are substantially more susceptible to motion and contact artefacts than ECG signals, and residual low frequency baseline wander or imperfect filtering can inflate short term interval variability precisely the pattern observed in the elevated PPG derived RMSSD of the present data. The relatively high absolute RMSSD values recorded in both modalities (170 ms ECG and 192 ms PPG) at a mean heart rate of 96 BPM are higher than typically reported resting values in the literature. Possible contributing factors include residual contact artefacts, minor baseline fluctuations that escaped the applied filters, the inherent timing jitter between the analog ECG and digital PPG channels, and the limited sophistication of real time filtering imposed by the microcontroller sampling constraints. These observations highlight the sensitivity of RMSSD to signal quality and reinforce the need for careful artefact management, particularly when using low cost hardware.

Recent comparative studies under controlled resting conditions have confirmed good to excellent agreement for mean heart rate and, to a lesser extent, SDNN, while RMSSD and other high frequency indices remain more labile, especially when posture changes or recording duration is short (Coste et al., 2025). Extending the acquisition window, as performed here, mitigates transient mismatches and yields summary statistics that are sufficiently close for educational and prototyping purposes.

A clinical grade Philips IntelliVue MX550 monitor was present in the recording environment and provided visual confirmation that heart rate and SpO<sub>2</sub> values were in a broadly similar range to those obtained by the low cost system (Figure 2). However, simultaneous quantitative data export and formal statistical agreement analysis (e.g., Bland Altman or ICC) were not performed and remain outside the scope of this technical demonstration.

Recent literature further supports the potential relevance of HRV monitoring in orthopedic and musculoskeletal contexts. Wearable derived HRV has been proposed as a practical adjunct for interpreting recovery capacity, autonomic stress, and load tolerance in outpatient orthopedic care (Flores et al., 2024). Reductions in HRV relative to an individual's baseline are increasingly viewed as markers of reduced physiologic reserve rather than direct predictors of injury. In parallel, studies in patients undergoing total knee arthroplasty (Gitler et al., 2024) and in athletes after musculoskeletal injury (Salama & Gadbois, 2024) have documented measurable changes in time and frequency domain HRV parameters during the perioperative and early recovery periods, suggesting that autonomic monitoring may provide complementary information about physiological stress and recovery trajectories. Although the present system was evaluated only under resting conditions in a single healthy subject, its low cost dual modality design offers a practical platform for future exploratory studies of physiological responses during orthopedic rehabilitation and early mobilization protocols.

The system's limitations must be clearly acknowledged. Data were collected from a single healthy adult under resting conditions only; hardware level temporal synchronisation between the analog ECG and digital PPG channels was imperfect; no simultaneous clinical grade reference recording with data export was available; and sampling rate constraints of the microcontroller limited the sophistication of real time filtering. These constraints are typical of low cost educational platforms. Consequently, the present work should be interpreted strictly as a technical feasibility and educational demonstration rather than as a validation study or evidence of clinical equivalence.

Taken together, the results demonstrate that a carefully engineered, low cost dual modality system can reproduce the well documented pattern of concordance (mean HR, SDNN) and residual divergence (RMSSD) between ECG and PPG derived metrics under resting conditions. By making both the raw signals and the derived parameters immediately visible on a live dashboard, the platform offers a tangible educational tool for understanding why PRV should not be treated as a direct surrogate for HRV an insight that has become increasingly important with the proliferation of consumer wearable devices (Kantrowitz et al., 2025; Ben David et al., 2026). While the current evaluation was limited to resting conditions in a single subject, the same architecture provides a practical foundation for future algorithm development, multimodal dataset construction, and exploratory investigations of physiological responses during orthopedic rehabilitation and early mobilization protocols.

## Conclusion

An end to end, Arduino based system for simultaneous real time acquisition and comparative analysis of ECG and PPG signals was successfully realized. The platform computes HR, SDNN, RMSSD, and SpO<sub>2</sub>, presents the results on a live dashboard, and supports the progressive construction of a custom multimodal dataset. The work illustrates the practical feasibility of low cost dual modality cardiac monitoring and confirms the residual differences that persist between electrical and optical methods, particularly in high frequency HRV metrics such as RMSSD.

While the current evaluation was limited to a single healthy subject under resting conditions, the system provides a practical educational and prototyping platform for biomedical signal processing. It may also serve as a foundation for future exploratory studies of physiological responses during orthopedic rehabilitation and early mobilization. The device is intended solely for educational, research prototyping, and digital health teaching purposes and is not a certified medical device.

Future work may include making the system fully portable and independent from a host computer by integrating a TFT display for real time visualization and wireless data transmission (e.g., ESP NOW or Bluetooth). Additional improvements could involve multi subject validation (including patients undergoing orthopedic rehabilitation), better hardware level temporal synchronization between the ECG and PPG channels, motion robust filtering for ambulatory and mobilization recordings, and the integration of additional physiological sensors. Expanding the custom dataset under both resting and dynamic conditions, performing formal agreement analyses against clinical grade monitors, and releasing the processing scripts as open source resources would further enhance the educational and research utility of the platform, particularly for studies exploring autonomic monitoring in orthopedic and musculoskeletal recovery contexts.

## Conflict of interest

The author declares no conflict of interest.

## Funding

This work received no external funding.

## Ethical statement

All measurements were performed by the author on herself under resting conditions for educational and technical demonstration purposes. No patient data were collected. The system is not a medical device.

## Data availability

Example session logs and processing scripts can be made available by the corresponding author upon reasonable request.

## AI usage statement:

During the preparation of this manuscript, generative AI tools (specifically Grok, developed by xAI) were used for language editing, structural suggestions, and improving the clarity of the Introduction and Discussion sections. All technical content, experimental design, data collection, signal processing implementation, and scientific interpretations were performed solely by the author. The author takes full responsibility for the accuracy and integrity of the work.

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