Real-Time ECG and HRV Monitoring in Handball Using a Low-Cost Wearable Sensor

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Abstract. The proliferation of wearable technology has revolutionized sports science, providing detailed insights into athlete performance and physical condition. However, the use of ECG in dynamic, high-contact sports like handball presents significant challenges. This paper introduces HeartTrack, an open-source wearable electrocardiogram (ECG) monitoring system designed specifically for monitoring athlete exertion in real-world sporting conditions. The system employs a distributed architecture based on the Message Queuing Telemetry Transport (MQTT) protocol for robust and decoupled data handling. Firstly, the system provides a real-time dashboard for the immediate visualization of the incoming ECG waveform alongside the calculated physiological parameters. Secondly, we report on a system validation study conducted during a handball training session, demonstrating the system's capability to quantify significant changes in cardiovascular metrics corresponding to player exertion. The key findings confirmed that the system could effectively track significant changes in heart rate and heart rate variability that correspond directly to varying levels of physical exertional activity. The system design and software is shared at: hearttrack.cloud.

Keywords: Wearable Sensors · Athlete Monitoring · Handball

1 Introduction

The proliferation of wearable technology has significantly advanced sports science, enabling more accessible insights into athlete performance and physical condition. While metrics like speed and distance, commonly tracked by GPS and accelerometers, offer valuable information about an athlete's external load, they often fail to capture the internal physiological load, which is the physiological response to the exercise performed. This internal load is critical for optimizing training, preventing overtraining, and reducing injury risk. Electrocardiography (ECG), which measures the heart's electrical activity, offers a direct measurement of the cardiovascular system's response to physical stress, making it a gold standard for assessing player exertion.

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However, the use of ECG in dynamic, high-contact sports such as handball poses significant challenges. Commercial systems are often expensive and function as proprietary "black boxes," limiting both data access and customization for researchers. In this work, we use the term dynamic sports to describe activities with irregular, high-intensity movement patterns and frequent body contact, for example handball, basketball, or rugby. These conditions generate far more severe motion artifacts than those typically observed in endurance sports like running or cycling. This distinction underlines why developing robust, low-cost ECG monitoring systems for these contexts is particularly challenging and necessary.

There is a clear need for accessible, open-source tools that allow researchers and practitioners to not only collect physiological data in these challenging environments but also to study and address these fundamental signal quality issues.

This paper introduces HeartTrack, an open-source wearable ECG system designed specifically for monitoring athlete exertion in real-world sporting conditions. Our contribution is threefold. First, we present the complete hardware and software design of the HeartTrack system, which is fully open-source to encourage adaptation and further development by the community. Second, we report on a system validation study conducted during a handball training session, demonstrating the system's capability to track meaningful trends in player exertion through heart rate monitoring. Third, we provide a crucial characterization of the primary limitation we encountered: the significant impact of motion artifacts on signal quality during high-intensity athletic movements.

By validating our system in a practical setting and transparently reporting on its limitations, we provide a realistic baseline for on-body ECG sensing in dynamic sports. This work serves as both a practical tool for sports scientists and a foundational study for future research aimed at developing robust algorithms to mitigate motion artifacts. This paper is structured as follows: We first review related work on wearable ECG systems and motion artifact challenges. We then detail the HeartTrack system architecture, followed by the methodology of our validation study. Subsequently, we present the results, focusing on both successful exertion tracking and the analysis of signal artifacts. Finally, we discuss the implications of our findings and outline future work to enhance the system's reliability.

2 Related Work

The foundation of this research rests on three key areas: the landscape of wearable ECG devices, the persistent challenge of motion artifacts in physiological sensing, and the specific application of monitoring player exertion in handball.

Wearable ECG devices are becoming increasingly prevalent for monitoring the cardiac activity of athletes and health-conscious individuals. Their potential for detecting arrhythmias and other cardiac events in real-world settings is significant [22,23]. Research has shown that these devices can be non-inferior to standard care for arrhythmia detection [10]. A variety of form factors exist, from user-friendly smartwatches and handheld devices to patches and mobile telemetry systems designed for continuous monitoring [4].

However, the scientific community acknowledges key limitations. Sanchis-Gomar et al. [23] highlight a scarcity of large-scale trials focused on identifying exercise-related arrhythmias with wearables. While popular devices like the Apple Watch and Fitbit have demonstrated acceptable heart rate accuracy in everyday conditions [17], recent studies confirm their accuracy declines significantly during intense exercise [14], especially for sensitive metrics like Heart Rate Variability (HRV) [3,8]. This gap underscores a critical need for standardized validation protocols to ensure the reliability of these devices in athletic contexts [21], a need that our present validation study of the HeartTrack system aims to address.

Our work is positioned within a landscape of diverse wearable sensors, each with distinct trade-offs for athletic monitoring. Commercial chest-strap systems, such as the Polar H10, are well-regarded for providing high-quality ECG data but function as proprietary "black boxes" that limit raw data access and customization for researchers. Consumer smartwatches, including the Apple Watch, offer user-friendly interfaces but primarily rely on photoplethysmography (PPG) for continuous heart rate monitoring, a method susceptible to motion artifacts during intense exercise. While they offer on-demand single-lead ECGs, they do not support continuous raw ECG streaming suitable for in-depth analysis. On the other end of the spectrum, open-source research platforms like BITalino [13,24] offer high flexibility and data access but at a substantially higher cost, with kits starting at over $149. The Heart Track system was specifically designed to fill a gap between these options, offering a unique combination of continuous 250 Hz ECG data streaming in a fully open-source framework at a hardware cost of approximately €18 per unit. This makes it a financially accessible and customizable tool for sports science researchers who require raw, high-resolution physiological data. The single greatest challenge to obtaining ECG data during physical activity is the presence of motion artifacts. These artifacts, caused by electrode movement and muscle contractions, can mask the underlying cardiac signal and make clinical interpretation or automated analysis unreliable. A significant body of research is dedicated to mitigating this noise.

Two primary approaches exist: wavelet-based methods and adaptive filtering. While wavelet transforms can be useful for improving signal correlation, they often introduce phase variability and are less suited for real-time applications [5,25]. In contrast, adaptive filtering algorithms have consistently shown superior performance. Studies have demonstrated that adaptive filters, particularly those utilizing the Least Mean Squares (LMS) algorithm and its variants (IPNLMS, PNLMS, BLMS), significantly outperform wavelet-based and traditional methods in reducing motion artifacts [2,7]. The use of a secondary sensor, such as an accelerometer, to provide a reference signal for the motion noise can further enhance the clarity of the filtered ECG signal [9]. Overall, adaptive filtering remains the state-of-the-art and preferred approach for motion artifact reduction in wearable ECG monitoring [1,18,20].

In dynamic team sports like handball, understanding player exertion is crucial for optimizing performance and training regimens. Research has consistently shown that physiological markers, particularly heart rate, are strongly linked to performance outcomes and vary significantly by playing position. For instance, studies have found that wing players often exhibit higher heart rates and superior aerobic capacity compared to backcourt players and pivots [11,16]. Conversely, backcourt players tend to cover more distance during matches, also resulting in high average heart rates [19].

Furthermore, research highlights the importance of repeated sprint and jumping ability, especially for wing players [12], and the negative correlation between body fat and running speed across all positions [6]. The consensus in the literature is that aerobic capacity is a key differentiator of performance among players [15]. This body of work underscores the clear need for position-specific training and validates the use of heart rate as a primary metric for assessing internal training load. Our study leverages these findings by validating an ECG-based system specifically within the demanding context of a handball training session.

3 The HeartTrack System

3.1 Hardware Design

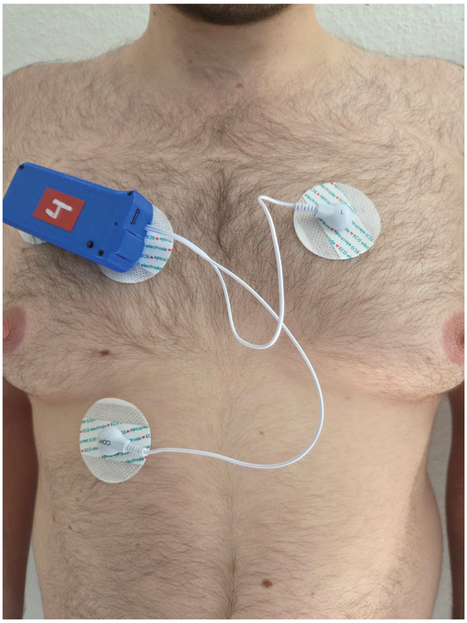

Fig. 1. The HeartTrack wearable sensor unit with electrode placement on a participant

A low-cost, wearable electrocardiogram (ECG) monitoring system was developed to capture, transmit, and analyze cardiac biopotentials. The data acquisition hardware is housed within a custom 3D-printed enclosure worn on the chest. It comprises an AD8232 analog front-end for ECG signal conditioning, which is subsequently digitized by a 16-bit ADS1115 analog-to-digital converter to ensure high-resolution signal capture. The sensor data is captured with a resolution of 250 Hz. An ESP32-based microcontroller (Lolin32 Lite) orchestrates device operations, including sensor interfacing and wireless communication. The firmware, developed in C++, is responsible for acquiring the digital ECG signal, checking sensor-body contact, monitoring battery levels, and synchronizing time with an NTP server to guarantee accurate timestamping for all data points.

3.2 System Architecture and Data Transmission

The system employs a distributed architecture based on the Message Queuing Telemetry Transport (MQTT) protocol for robust and decoupled data handling. The wearable device connects to the network via Wi-Fi and publishes the raw, timestamped ECG data, formatted as a JSON object, to a central MQTT broker. This broker disseminates the information to two independent client applications. The first client is a Python script that subscribes to the raw data feed. This script utilizes the Neurokit2 library to perform real-time signal processing, including signal cleaning, R-peak detection, and the subsequent calculation of heart rate (BPM) and heart rate variability (HRV) metrics. These computed features are then published back to the MQTT broker on a separate topic.

3.3 Real-Time Processing and Visualization

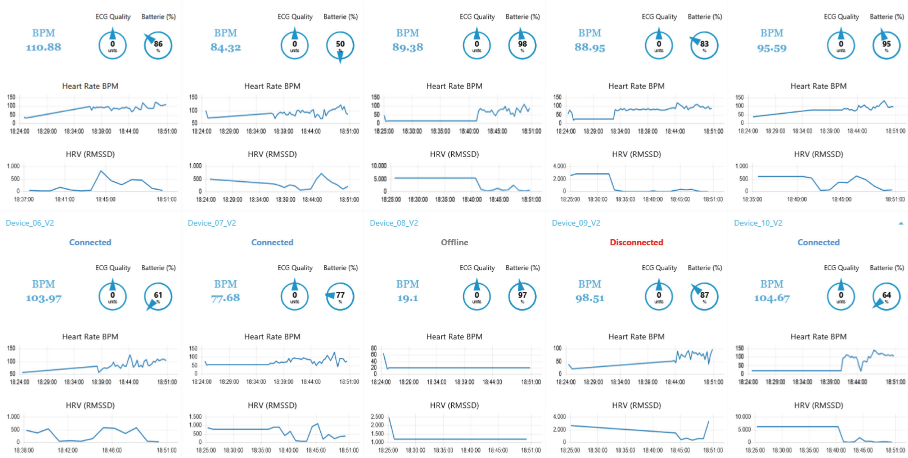

Fig. 2. The real-time monitoring dashboard built in Node-RED, displaying data from nine concurrent participants (Color figure online)

Concurrently, a second client, built on the Node-RED platform, subscribes to both the raw data and the processed-data topics from the MQTT broker. This component serves a dual purpose. Firstly, it provides a real-time dashboard (see 2) for the immediate visualization of the incoming ECG waveform alongside the calculated physiological parameters. Secondly, it ensures data persistence by systematically logging the raw, timestamped ECG signal to a comma-separated values (CSV) file, making the complete dataset available for comprehensive offline analysis.

4 Results

The developed wearable ECG system was deployed to monitor cardiovascular dynamics during a 75-minute training session with a female handball team. Data collection was attempted for 10 athletes, with nine of the ten sensor units functioning correctly throughout the entire session, resulting in a 90% success rate for data acquisition. One unit failed to maintain a stable connection mid-session and its data was excluded from further analysis. The nine complete datasets were successfully correlated with a concurrent video recording of the training, which enabled the annotation of distinct activity phases: a running warm-up, static stretching, specific handball drills, and scrimmage play.

Analysis of the acquired data revealed distinct physiological responses corresponding to the annotated training phases. During the initial low-intensity stretching period, baseline heart rate (BPM) values were stable. The subsequent running warm-up elicited a steady, progressive increase in heart rate across all participants. For example, the average BPM rose from a baseline of approximately 75 BPM to 140 BPM by the conclusion of the warm-up. This was accompanied by a statistically significant decrease in Heart Rate Variability (RMSSD), from a mean of 45±10 ms during stretching to 12±5 ms during scrimmage play ($p < .001$).

The most dynamic cardiovascular responses were observed during the high-intensity drills and scrimmage play. During these periods, the system recorded rapid fluctuations in heart rate, with peak values for some athletes exceeding 180 BPM during intense, game-like situations. The real-time dashboard provided immediate visualization of these rapid fluctuations in heart rate. Concurrently, HRV metrics were significantly suppressed throughout these high-exertion phases, reflecting the high physiological stress of the sport. Despite the vigorous, high-impact movements inherent to handball, the nine functional units consistently captured ECG waveforms, and the complete, timestamped raw data was reliably logged to CSV files for each athlete, providing a comprehensive dataset for detailed post-session analysis.

4.1 Motion Artifact Characterization

In line with the third contribution of this work, this section provides a characterization of the impact of motion artifacts on signal quality. Figure 3 (top) displays

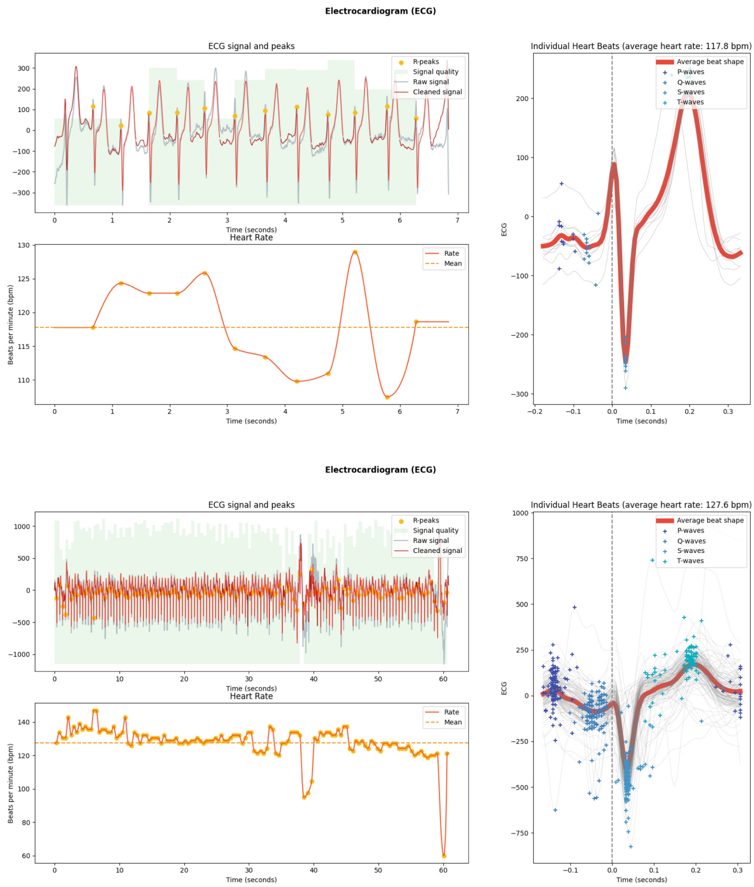

Fig. 3. Representative ECG data segments. (Top) A 7-second recording during a warm-up, showing a clean signal and stable heart rate (around 118 BPM). (Bottom) A 60-second recording during a high-intensity game scene, showing significant motion artifacts and an erratic, higher heart rate (around 127.6 BPM)

a 7-second segment from a participant during the running warm-up, illustrating a period of high signal quality. The data is characterized by high signal quality and a clean, consistent ECG morphology, with clearly discernible P, QRS, and T waves. The corresponding heart rate is elevated but stable at approximately 118 BPM, which is indicative of steady-state aerobic exercise. The overlay of individual heartbeats shows minimal variation, confirming the high fidelity of the signal captured during controlled movement. This is contrasted with Fig. 3 (bottom), which shows a segment heavily affected by motion artifacts during high-intensity gameplay. This recording reflects the challenges of data acquisition in a dynamic sporting environment. The signal exhibits significant motion artifacts, leading to periods of degraded quality, particularly around the 40-second mark. The heart rate is not only higher on average (127.6 BPM) but also highly erratic, fluctuating rapidly in response to the unpredictable demands of the game. The wide scatter of the overlaid individual heartbeats is a result of both this physiological variability and the residual noise in the signal. These figures visually confirm that while the system can capture the high-intensity cardiovascular response to gameplay, data quality is inherently more variable compared to more controlled exercise conditions.

5 Discussion

The primary goal of this project was to develop and validate a low-cost, wearable ECG system in a demanding, real-world athletic environment. The results confirm that the system successfully captured physiological data with enough fidelity to differentiate between training phases. The successful acquisition of nine complete datasets over 75 min, despite the high-impact and dynamic nature of the sport, underscores the viability of using inexpensive, custom-built hardware for field-based research.

The quantitatively distinct cardiovascular responses across various training phases, from the stable, elevated heart rate during the warm-up to the erratic, peak responses during scrimmage play, highlights the system's sensitivity to changing metabolic demands. The statistically significant decrease in RMSSD between low- and high-intensity phases, quantitatively confirms the expected swing in autonomic nervous system balance. This demonstrates that the captured data aligns with established physiological principles (e.g., an increase in heart rate and a decrease in heart rate variability with rising exercise intensity), which allows for valid physiological interpretation. The accompanying video annotations proved invaluable, providing the necessary context to move beyond simple data logging toward a quantitative analysis of athlete physiology in response to specific stimuli.

However, the study also revealed important limitations. The failure of one of the ten sensor units serves as a crucial reminder of the reliability challenges inherent in low-cost electronics compared to medical-grade equipment. Furthermore, the motion artifacts observed in the data during high-intensity gameplay, as illustrated in the results, are a significant consideration. While the cleaning algorithms from the Neurokit2 library were effective, periods of severe noise can obscure the underlying signal, potentially affecting the accuracy of beat detection and subsequent HRV calculations. This highlights a critical trade-off between cost, wearability, and signal fidelity in extreme motion contexts. While this study focused on validating the physiological data capture, a quantitative evaluation of the MQTT data transmission characteristics (e.g., latency, packet loss) or a direct comparison of different signal filtering algorithms was outside the scope of this initial validation. These remain important areas for future technical evaluation. We acknowledge that this study was conducted with an all-female cohort. Future work should include male athletes to investigate potential differences in signal quality related to chest anatomy and electrode placement.

Furthermore, the current prototype shown in Fig. 1, while functional for a single session, requires further refinement to improve long-term comfort and robustness for longitudinal studies. Future work should focus on addressing these limitations. Improvements to the hardware, such as a more robust enclosure design and the use of advanced motion-cancellation electrodes, could mitigate artifacts. On the software side, implementing more sophisticated, real-time artifact detection and signal reconstruction algorithms could further enhance data quality. Additionally, future studies could leverage this system to investigate more complex research questions, such as quantifying training load, monitoring athlete fatigue over a season, or providing real-time biofeedback to coaches and players. Taken together, these findings map directly to the three contributions outlined in the introduction. First, the open-source nature of HeartTrack makes it a reusable platform for both applied sports monitoring and methodological research, filling a gap left by closed commercial systems. Second, our validation study during a real-world handball training session demonstrated that despite the challenges of high-intensity motion, the system reliably tracked meaningful trends in heart rate and HRV, confirming its practical usability for exertion monitoring. Third, our analysis of motion artifacts provides a transparent characterization of the system's primary limitation, offering a realistic baseline for future algorithmic improvements.

6 Conclusion

This study successfully demonstrated the design, implementation, and validation of a wearable, low-cost ECG monitoring system. The system proved capable of capturing and analyzing cardiovascular data from athletes during a live handball training session. The key findings confirmed that the device could effectively track significant changes in heart rate and heart rate variability that correspond directly to varying levels of physical exertion. Despite challenges related to motion artifacts and hardware reliability, the project establishes a framework for applying affordable, custom-built sensor technology in applied sports science. This work provides a foundation for future research into accessible, field-based physiological monitoring, potentially enabling more widespread and frequent analysis of athlete performance and well-being.

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