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An IoT-Based Real-Time Monitoring System for Intradialytic Cycling in Hemodialysis Patients

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ABSTRACT

Patients undergoing hemodialysis often experience reduced physical capacity, muscle weakness, and increased cardiovascular risk due to prolonged inactivity during treatment sessions. Intradialytic exercise, particularly stationary cycling, has been recommended as an effective intervention to improve physical function and cardiovascular health in this population. However, conventional monitoring methods remain limited, often relying on manual observation and sporadic measurements that cannot provide continuous physiological feedback. This study proposes an Internet of Things (IoT)-based real-time health-monitoring system to support intradialytic cycling exercise. The proposed system integrates multiple biomedical sensors, including a MAX30102 sensor for heart rate and oxygen saturation monitoring, a Hall-effect sensor for pedal rotation detection, and electrocardiography electrodes for assessing leg muscle activity. Physiological data are processed using a Raspberry Pi platform and transmitted to a web-based monitoring interface that enables real-time visualization for medical personnel. The system also incorporates patient-specific parameters such as age, height, weight, and exercise duration to estimate caloric expenditure using the metabolic equivalent of task (MET) model. To ensure operational reliability, the platform supports both cloud-based data transmission and local offline storage. Experimental validation was conducted using three participants representing different age groups and health conditions. The results demonstrate that the system can effectively capture real-time physiological responses and detect variations in exercise intensity among individuals. The proposed approach provides a practical solution for continuous intradialytic exercise monitoring and has the potential to improve exercise safety and personalized rehabilitation strategies for hemodialysis patients.

1. INTRODUCTION

Chronic kidney disease (CKD) is a growing global health issue, with hemodialysis being a vital life-sustaining therapy for patients in the end-stage of renal failure [1]. Despite its therapeutic benefits, hemodialysis is associated with reduced physical function, muscle wasting, and increased cardiovascular risk due to prolonged sedentary periods during treatment sessions [2]. To mitigate these complications, intradialytic exercise, such as stationary biking, has been increasingly recommended as a safe and effective strategy to improve physical capacity and cardiovascular health in hemodialysis patients [3]. Evidence supports the effectiveness of intradialysis static bike exercise in improving the functional capacity of hemodialysis patients [4], underscoring its therapeutic potential.

Intradialytic cycling, however, requires close monitoring of the patient's physiological status to ensure safety and effectiveness, especially considering the dynamic hemodynamic changes that occur during dialysis [5]. Conventional monitoring methods are often manual, sporadic, and prone to delay in response, thereby limiting the precision of exercise adjustments and real-time risk mitigation [6]. This underscores the urgent need for a reliable and continuous monitoring system integrated directly into the exercise modality [7].

The Internet of Things (IoT) has revolutionized healthcare by enabling real-time monitoring, remote data transmission, and intelligent decision-making through sensor integration and cloud computing [8]. In recent years, IoT-based systems have been successfully implemented in various health monitoring applications, including cardiac telemetry, glucose monitoring, and rehabilitation support [9]. These advancements offer a promising avenue for integrating IoT solutions into dialysis settings to track physiological signals such as heart rate, blood pressure, oxygen saturation, and cycling metrics in real time [10].

Although several studies have introduced IoT-enabled health monitoring systems for general patient care, few have specifically addressed the unique challenges of intradialysis exercise. Prior work either lacks integration with physical activity tools such as stationary bikes, does not provide real-time feedback, or focuses only on non-dialysis populations [11]. Moreover, current systems are limited in their ability to adaptively respond to abnormal physiological changes during exercise, particularly in vulnerable patient groups such as those undergoing hemodialysis [12].

To bridge this gap, this study proposes a novel IoT-based real-time health-monitoring system designed explicitly for intradialysis exercise on a stationary bike. The proposed system integrates multiple biomedical sensors, including a MAX30102 for heart rate and oxygen saturation monitoring, a Hall-effect sensor for pedal rotation tracking, and ECG electrodes for monitoring leg muscle activity [13]. These sensors are connected to a web-based application, InoCycle, that enables medical personnel to visualize and monitor real-time data. The system is designed to operate in two network modes: an internet-based mode, where data is transmitted to a cloud server for remote access, and a local network mode, where the Raspberry Pi functions as an internal server for environments with limited internet access.

By developing this system, this study aims to fill the research gap in intradialysis exercise monitoring by offering a comprehensive multi-sensor tracking system that can simultaneously monitor heart rate, oxygen saturation, pedal rotations, calories burned, and leg muscle activity. Additionally, the dual-mode network configuration ensures adaptability across different healthcare settings, providing reliable data access regardless of network conditions. The InoCycle platform enables medical personnel to make data-driven decisions in real-time, ensuring personalized, safe exercise adjustments for dialysis patients.

2. THE PROPOSED METHOD

This study proposes a real-time IoT-based health-monitoring system for intradialysis exercise on a stationary bike. The system is designed to continuously track physiological and user profile data while providing real-time visualization for medical personnel. The architecture comprises three main components: sensor modules, a data processing unit, and a web-based monitoring platform, as illustrated in Figure 1.

The sensor modules collect real-time physiological data, including heart rate [14], oxygen saturation [15], pedal rotations, and leg muscle activity [16]. These values are measured using three biomedical sensors: the MAX30102 optical sensor for heart rate and SpO_2 monitoring [17], a Hall Effect Sensor (3144E) to track pedal rotations [18], and ECG electrodes to measure leg muscle activity [19, 20]. In addition to physiological data, the system collects user profile data, including height, weight, age, name, and exercise duration. The integration of user profile data allows the system to personalize exercise tracking and provide an accurate estimation of caloric expenditure during workouts.

$$\text{Calories Burned} = \text{MET} \times \text{Weight} \times \text{Exercise Duration} \quad (1)$$

To estimate the number of calories burned during the intradialysis cycling session, the system applies the following formula 1 [21]. In this equation, the calories burned represent the total energy expenditure in kilocalories (kcal) and are influenced by several factors. One key factor is the Metabolic Equivalent of Task (MET), a standardized value used to estimate the energy cost of physical activities, which is set at 3.5 for cycling during dialysis [22]. Another contributing factor is the individual's weight, measured in kilograms, as heavier individuals tend to expend more energy for the same activity [23]. Additionally, exercise duration determines the total time spent pedaling, with predefined choices of 20, 40, or 60 minutes, allowing for different levels of workout intensity [24].

The data processing unit, implemented on a Raspberry Pi, is responsible for filtering, analyzing, and transmitting sensor data in real-time [25]. The Raspberry Pi collects data via I^2C and GPIO interfaces, ensuring seamless integration between hardware components [26]. To enhance signal accuracy and reduce noise, multiple filtering techniques are applied [27]. The MAX30102 sensor outputs photoplethysmography (PPG) signals, which are processed with a Butterworth low-pass filter to remove motion artifacts before the Fast Fourier Transform (FFT) is applied to estimate heart rate and oxygen saturation [28]. The Hall Effect Sensor detects each pedal revolution, and a moving average filter is used to smooth out variations in cadence [29]. For ECG signals, a band-pass filter (0.5–100 Hz) is applied to eliminate baseline drift and high-frequency noise, followed by Root Mean Square (RMS) processing to estimate muscle contraction intensity [30]. These filtering and signal-processing techniques ensure that only clean, relevant physiological data are transmitted for visualization [31].

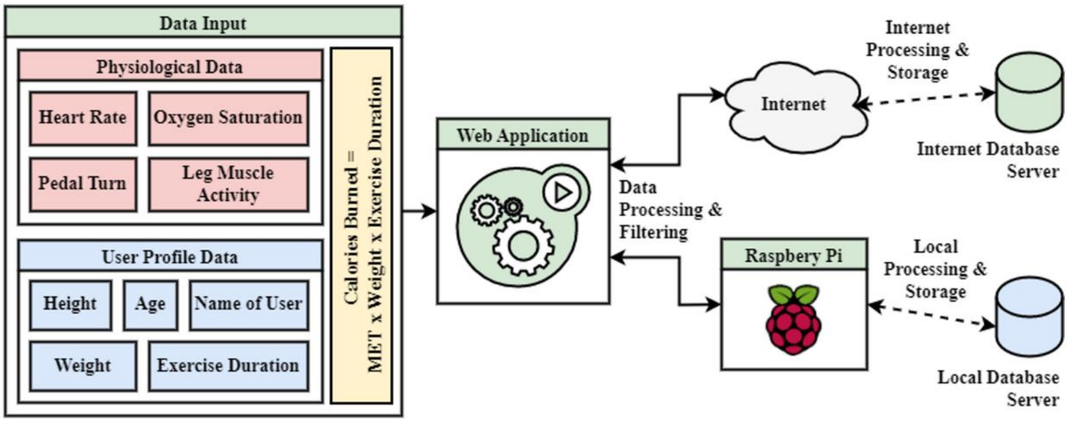


Figure 1. The proposed method

After processing, the system transmits the collected data to InoCycle, a web-based application that serves as the real-time data visualization and monitoring platform for medical personnel. To ensure adaptability in various healthcare settings, the system supports two network configurations: internet-based mode and local network mode. In the internet-based mode, data is transmitted to an Internet Database Server, enabling healthcare providers to monitor patient progress from external systems. Meanwhile, in local network mode, the Raspberry Pi functions as a local server, enabling offline data storage and analysis when internet access is unavailable. When connectivity is lost, the system temporarily stores data in the Raspberry Pi's local storage and automatically synchronizes it with the cloud server once internet access is restored.

Figure 1 illustrates how physiological and user profile data are processed, transmitted, and stored based on the available network configuration. The integration of real-time multi-sensor monitoring, a dual-mode network architecture, and web-based visualization ensures the system remains adaptable across various healthcare settings. This system provides a comprehensive monitoring solution for intradialysis exercise, addressing the lack of physiological tracking in current intradialysis programs while enabling personalized patient care and real-time supervision by medical personnel. This approach aligns with the implementation of web-based healthcare systems that allow data upload and real-time result display, as demonstrated in similar IoT-health applications [32].

3. RESEARCH METHOD

This study employed a proof-of-concept pilot experimental setup to evaluate the functionality and feasibility of the proposed system. While the small sample size (n=3) limits generalizability, it demonstrates initial system validation and captures preliminary physiological trends across varied user profiles.

To evaluate the effectiveness of the proposed system, a controlled experimental setup was conducted to monitor physiological responses during intradialysis exercise using a stationary bike. The study involved three participants aged 23, 43, and 53 years, each representing different physical conditions. Before starting the exercise session, participants were required to input their name, height, weight, age, and exercise duration into the system interface, as depicted in Figure 2. These inputs were essential for the system to personalize exercise tracking and estimate caloric expenditure using the predefined Metabolic Equivalent of Task (MET) formula. Once the user data was recorded, the system initiated real-time physiological monitoring, capturing heart rate, oxygen saturation, pedal rotations, and leg muscle activity through integrated sensors.

During the exercise, the system continuously collected physiological data and applied signal processing techniques to filter noise and extract meaningful health indicators. The MAX30102 sensor measured heart rate and SpO_2 levels, while the Hall Effect Sensor recorded pedal rotations to determine exercise intensity. Additionally, ECG electrodes captured leg muscle activity, providing insights into neuromuscular responses during intradialysis exercise. The system also computed caloric expenditure based on the formula Calories Burned = MET × Weight × Exercise Duration, ensuring that energy output was tracked accurately in real time.

Once data acquisition was complete, the system checked for an internet connection before storing and visualizing the collected data. If an internet connection was detected, the processed data was uploaded to the Internet Database Server, allowing remote access for healthcare providers to monitor exercise performance through a computer interface. However, if no internet access was available, the system stored the data locally on the Raspberry Pi's Local Database Server, ensuring uninterrupted monitoring. The visualization interface remained accessible through the Raspberry Pi, providing direct feedback via a local display system. This adaptive storage mechanism, as illustrated in Figure 2, enabled seamless data handling across varying network conditions, ensuring patient monitoring was not disrupted.

To validate the accuracy of the proposed system, sensor readings were compared with those from commercially available medical-grade devices used to monitor heart rate, oxygen saturation, and muscle activity. The MAX30102 sensor's heart rate and SpO_2 readings were cross-referenced with a clinically approved pulse oximeter, such as the Omron CMS50D, to verify consistency and accuracy. Similarly, the ECG sensor's measurements of muscle activity were evaluated against a standard electromyography (EMG) system to ensure that contraction intensities were correctly captured. Data from each experimental session, which lasted 20 minutes, was analyzed to assess the reliability of the system in measuring real-time physiological responses.

Performance evaluation criteria included data accuracy, transmission speed, real-time responsiveness, and system reliability under different network conditions. Sensor measurements were compared statistically with reference devices using mean absolute error (MAE) and Pearson's correlation coefficient to assess how closely the system's readings aligned with those of clinical-grade monitoring tools. The results from these experiments provided insights into the system's capability to deliver accurate and reliable physiological data for intradialysis exercise monitoring. The findings were used to assess the system's potential for wider clinical adoption, demonstrating that integrating IoT-based real-time monitoring could enhance patient safety and exercise effectiveness during hemodialysis.

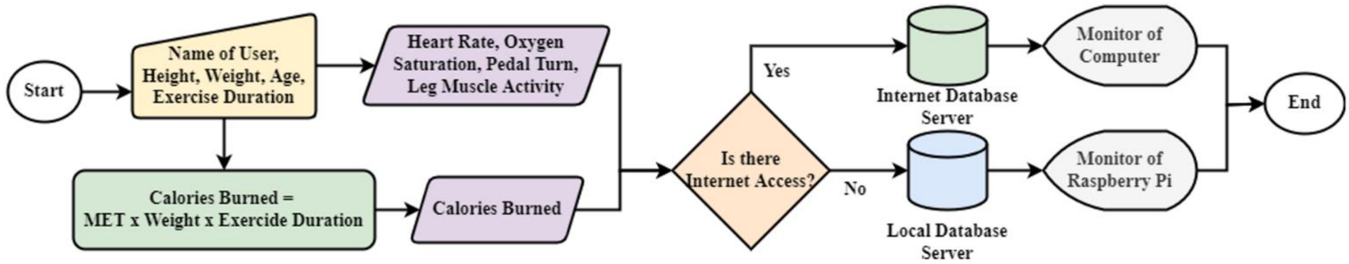


Figure 2. The steps of a real-time health monitoring system

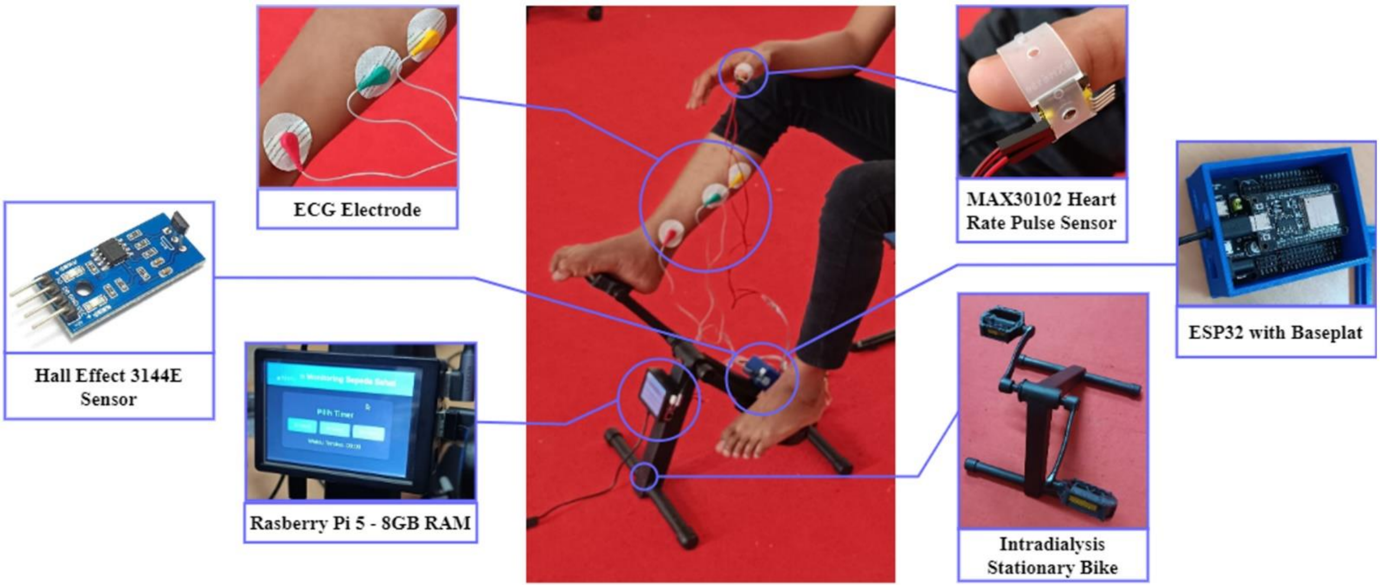


Figure 3. Main components of the system

4. RESULT AND DISCUSSION

This section presents the experimental results obtained from testing the proposed IoT-based health monitoring system on three respondents with different physiological characteristics. The discussion focuses on system accuracy, real-time data processing capabilities, and comparison with existing monitoring methods. The experimental evaluation involved three participants aged 23, 43, and 53 years old, representing different age groups and health conditions, including one respondent diagnosed with CKD.

4.1 Result

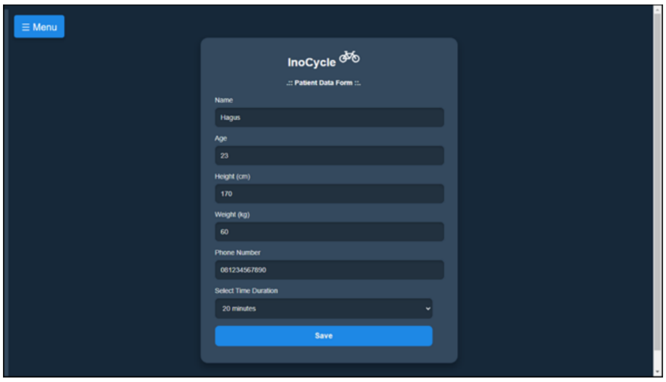
4.1.1 System implementation and performance evaluation

The IoT-based intradialysis exercise monitoring system consists of multiple hardware and software components, as illustrated in Figure 3. The system integrates biomedical sensors, including the MAX30102 Heart Rate Pulse Sensor for heart rate and oxygen saturation measurement, an ECG Electrode for leg muscle activity detection, and a Hall Effect 3144E Sensor for pedal rotation tracking. The system is controlled by a Raspberry Pi 5 (8GB RAM), which processes and transmits the collected data in real-time. A web-based application interface (InoCycle) powered by an ESP32 module enables users and healthcare professionals to remotely monitor exercise parameters.

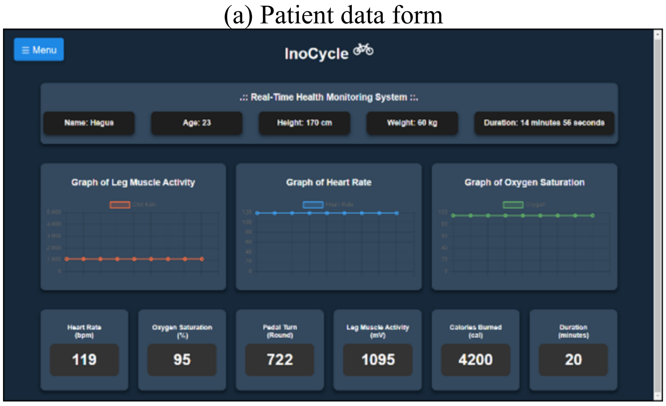
4.1.2 Experimental results and data analysis

The system was tested on three respondents, each performing a 20-minute intradialysis cycling session while their physiological parameters were recorded. The test results for each respondent were analyzed separately to observe variations in exercise intensity, physiological responses, and caloric expenditure.

Test Results for Respondent 1 (23 years old, healthy condition). Figure 4(a) shows the patient data form interface on the InoCycle web application, where users input personal details such as name, age, height, weight, and exercise duration before beginning the session. Figure 4(b) presents the real-time monitoring interface, displaying heart rate, oxygen saturation, pedal rotations, leg muscle activity, and caloric expenditure. The graphical visualization facilitates continuous monitoring, enabling medical personnel to track exercise performance dynamically.



(a) Patient data form



(b) Real-time health monitoring system

Figure 4. Web application view of respondent 1

Based on Figure 5 and the test results table, the data shows changes in physiological parameters and performance during 20 minutes of stationary bike exercise. Heart rate increased gradually from 85 bpm in the first minute to 123 bpm in the 20th minute, reflecting a normal cardiovascular response to exercise. Oxygen saturation remained stable at 94-95%, indicating that oxygen supply was sufficient throughout the session. Pedal rotations increased linearly, reaching 2400 revolutions by the end of the exercise, while leg muscle activity increased from 1000 mV to 1190 mV, corresponding to the progressive engagement of muscle fibers. Calories burned also increased consistently from 3.5 kcal in the first minute to 70 kcal by the end of the session. These findings suggest that the participant maintained optimal exercise intensity, demonstrating a healthy physiological response to physical exertion.

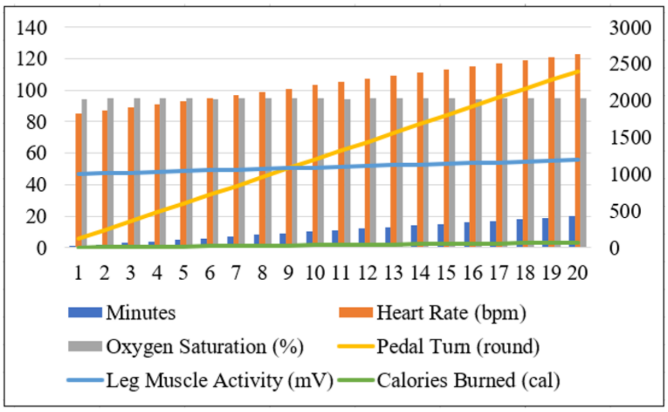


Figure 5. The test results of respondent 1 (23 years old)

Test Results for Respondent 2 (43 years old, healthy condition). Figure 6 displays the real-time health monitoring interface for Respondent 2, aged 43, with a height of 172 cm and a weight of 62 kg. During the 20-minute session, heart rate was 108 bpm, and oxygen saturation remained stable at 96%. The number of pedal rotations reached 1430, with leg muscle activity measured at 1180 mV. The total calories burned were 47 kcal, suggesting a moderate-intensity workout for this respondent.

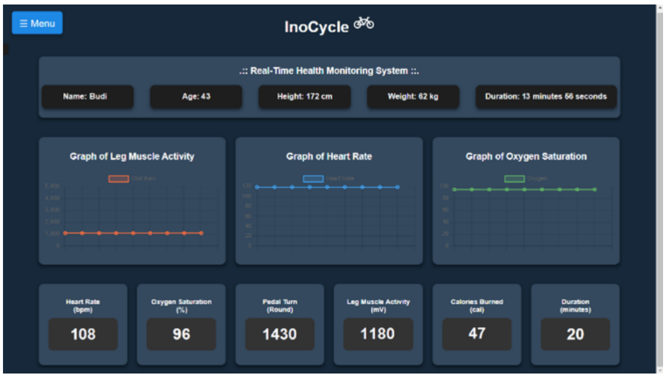


Figure 6. Real-time health monitoring system of respondent 2 (43 years old)

Based on Figure 7 and the test results table, heart rate increased from 90 bpm in the first minute to 118 bpm in the 20th minute, indicating a gradual cardiovascular adaptation to exercise. Oxygen saturation remained stable in the range of 95-96%, ensuring sufficient oxygen availability. Pedal rotations increased linearly, reaching 2200 revolutions at the end of the session, while leg muscle activity increased from 1000 mV at the beginning to 1285 mV at the end. Calories burned increased steadily from 3.6 kcal to 72.3 kcal, demonstrating that caloric expenditure was proportional to the exercise duration and intensity. These findings indicate that middle-aged individuals can sustain prolonged exercise sessions with stable physiological responses.

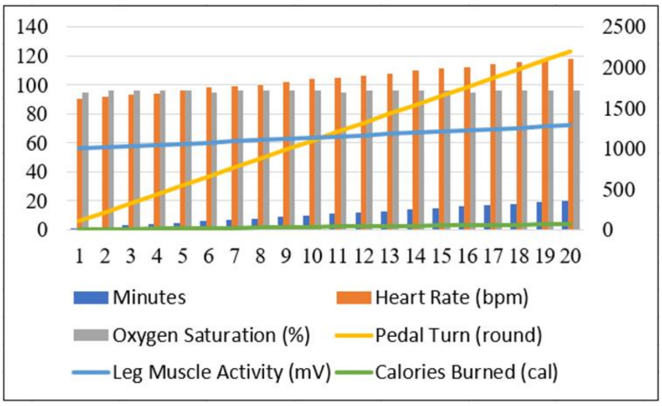


Figure 7. The test results of respondent 2 (43 years old)

Test Results for Respondent 3 (53 years old, diagnosed with chronic kidney disease). Figure 8 illustrates the real-time monitoring interface for Respondent 3, a 53-year-old individual diagnosed with CKD. Heart rate was 92 bpm, and oxygen saturation was 93%. The total number of pedal rotations was 1100, with leg muscle activity measured at 1050 mV. The respondent burned 34 kcal during the 20-minute session, indicating lower exercise capacity than the younger participants.

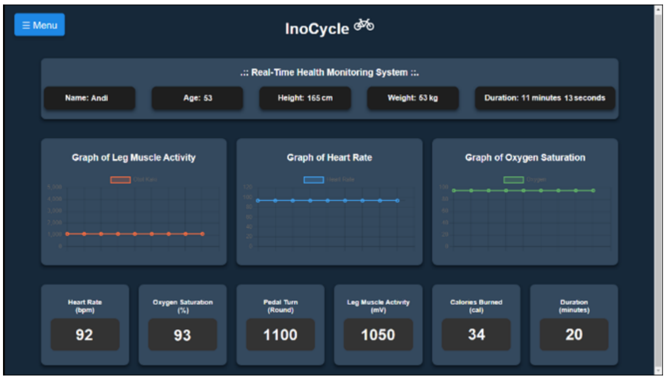


Figure 8. Real-time health monitoring system of respondent 3 (53 years old)

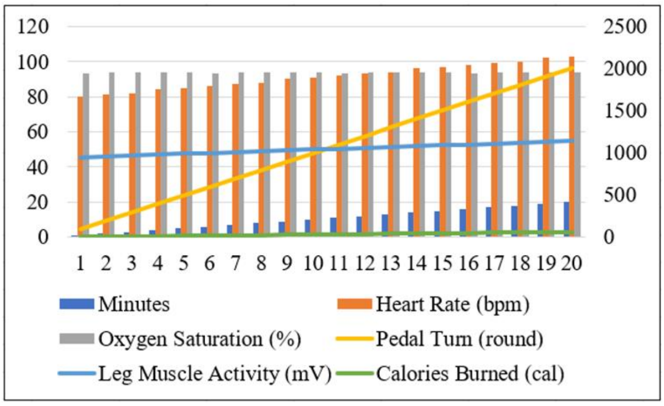


Figure 9. The test results of respondent 3 (53 years old with kidney disease)

Figure 9 and the test results table indicate that heart rate increased from 80 bpm in the first minute to 103 bpm in the 20th minute, with a lower peak compared to the younger respondents. Oxygen saturation remained stable at 93-94%, demonstrating that oxygenation was maintained despite potential physiological limitations. Pedal rotations increased progressively, reaching 2000 by the end of the session, while leg muscle activity increased from 950 mV to 1140 mV. Calories burned increased from 3.1 kcal to 61.8 kcal, showing a lower energy expenditure likely due to reduced exercise intensity. These findings highlight the potential impact of muscle fatigue and cardiovascular limitations in CKD patients, reinforcing the need for personalized exercise prescriptions in this population.

Table 1 summarizes the physiological responses of the three respondents during the 20-minute intradialysis exercise session. The recorded parameters include heart rate, oxygen saturation, pedal turns, leg muscle activity, and caloric expenditure. The data reveals significant differences in physical performance between respondents based on age and health condition.

Table 1. The value of the respondent test results

Parameter	Respondent 1	Respondent 2	Respondent 3
Heart Rate (bpm)	123	118	103
Oxygen Saturation (%)	95	96	94
Pedal Turn (round)	2400	2200	2000
Leg Muscle Activity (mV)	1190	1285	1140
Calories Burned (cal)	70	72.3	61.8

Respondent 1 (23 years old, healthy) demonstrated the highest exercise intensity, with a peak heart rate of 123 bpm and the highest number of pedal turns (2400 rounds). The oxygen saturation remained stable at 95%, indicating optimal oxygen supply during the session. Leg muscle activity also reached the highest value (1190 mV), reflecting greater neuromuscular engagement. Consequently, this respondent burned 70 kcal, suggesting a higher energy expenditure due to increased exercise intensity.

Respondent 2 (43 years old, healthy) showed slightly lower exercise performance compared to Respondent 1, with a maximum heart rate of 118 bpm and a total of 2200 pedal turns. Oxygen saturation remained stable at 96%, suggesting efficient oxygen utilization. Leg muscle activity was recorded at 1285 mV. The system successfully captured the variation in signal amplitude between individuals, which may correspond to different levels of neuromuscular output or exercise effort. The total calories burned were 72.3 kcal, slightly higher than those of Respondent 1, which may be attributed to the respondent's greater body weight.

Respondent 3 (53 years old, diagnosed with chronic kidney disease) exhibited lower exercise capacity, with a peak heart rate of 103 bpm and the lowest number of pedal turns (2000 rounds). Oxygen saturation was the lowest among the three respondents at 94%, likely due to the respondent's underlying health condition. Leg muscle activity was also the lowest at 1140 mV, indicating reduced neuromuscular activation. The total calories burned were 61.8 kcal, the lowest among the three respondents, suggesting that the reduced exercise intensity resulted in lower energy expenditure.

These results highlight the impact of age and health conditions on exercise performance. Younger, healthier respondents exhibited higher cardiovascular and muscular activity, whereas the CKD patient showed lower physical endurance, reinforcing the need for personalized exercise prescriptions based on real-time physiological monitoring. The findings also suggest that real-time tracking of heart rate, oxygen saturation, and muscle activity can assist medical personnel in adjusting exercise intensity to prevent overexertion, particularly for patients with chronic conditions.

4.1.3 System validation against medical-grade devices

To substantiate the accuracy of the proposed system, sensor readings were rigorously compared with those from certified medical-grade devices. Heart rate (HR) and oxygen saturation (SpO_2) measurements from the MAX30102 sensor were validated against a clinically approved pulse oximeter (Omron CMS50D). Simultaneously, the leg muscle activity signals from the ECG electrodes were compared with a reference electromyography (EMG) system (Biopac MP36). Data were collected synchronously during the 20-minute exercise sessions for all three respondents. The agreement between the prototype system and the reference devices was quantified using Mean Absolute Error (MAE) and Pearson Correlation Coefficient (r), as summarized in Table 2.

Table 2. System validation results against medical-grade reference devices

Physiological Parameter	Reference Device	Mean Absolute Error (MAE)	Pearson Correlation (r)
Heart Rate (HR)	Omron CMS50D	2.4 bpm	0.98
Oxygen Saturation (SpO_2)	Omron CMS50D	1.2 %	0.96
Leg Muscle Activity (RMS)	Biopac MP36 EMG	85 mV	0.94

The low MAE values and strong positive correlations ($r > 0.94$) across all parameters confirm that the proposed IoT system provides measurements that closely match those in established medical equipment, thereby validating its accuracy for real-time physiological monitoring.

4.2 Discussion

While previous IoT-based health monitoring systems have demonstrated utility in general patient care [9, 15], their application in the specific, high-risk context of intradialysis exercise has been limited. Prior systems often focus on post-exercise vitals monitoring or single-parameter tracking (e.g., heart rate alone) [16], lacking the comprehensive, concurrent multi-sensor integration required for safe exercise supervision during hemodialysis. Moreover, solutions proposed for dialysis settings often focus on general patient monitoring [10] but fail to integrate directly with exercise equipment [11], thereby missing the opportunity for real-time, dose-controlled intervention. Our system directly addresses these gaps by fusing data from cardiovascular (MAX30102), biomechanical (Hall Effect), and neuromuscular (ECG) sensors into a single, real-time stream, physically embedded within the stationary bike. This holistic, integrated approach represents a significant departure from prior work and is specifically tailored to mitigate the unique hemodynamic risks of exercise during dialysis [12].

The observed physiological trends align with established literature on exercise capacity in CKD. The notably lower pedal rotations (2000 rounds) and attenuated heart rate response (peak 103 bpm) in our CKD patient (Respondent 3) are consistent with the exercise intolerance documented in uremic myopathy and cardiovascular dysfunction [33]. This demonstrates the system's sensitivity in capturing the diminished exercise capacity characteristic of this population.

The real-time feedback from this sensor array helps identify hemodynamic or muscular instability, which is critical in intradialysis settings where patients often experience blood pressure fluctuations and fatigue. The use of the Hall Effect sensor to track pedal rotation also enables objective quantification of exercise intensity—a key metric often missing in conventional intradialytic exercise programs.

Compared to existing IoT-based health monitoring systems, which often focus on isolated parameters or post-hoc analysis [9, 16], the proposed system offers a comprehensive, concurrent multi-sensor approach. This enables simultaneous, real-time monitoring of interdependent physiological streams (cardiovascular, muscular, and performance metrics), a capability absent in prior intradialysis-specific proposals [11]. Furthermore, the dual-mode (online/offline) data storage architecture ensures operational resilience in clinical environments with unstable connectivity, a practical advancement over systems reliant solely on cloud infrastructure [10, 15].

Intradialytic exercise (IDE), particularly cycling, has been associated with improved dialysis efficiency, physical capacity, and patient-reported outcomes. However, its clinical adoption remains limited due to safety concerns, particularly regarding cardiovascular stability during sessions. The proposed system addresses this issue by enabling real-time tracking of vital signs, including heart rate, blood pressure, oxygen saturation, and cycling cadence, thereby ensuring the exercise remains within safe physiological thresholds. Our system enables automated alerts and remote supervision, reducing nursing burden and mitigating risks associated with manual monitoring. This aligns with findings by Maniam et al. [34], who demonstrated that IoT-based systems improve responsiveness in dialysis settings.

The results demonstrate that the proposed system provides real-time, multi-sensor physiological monitoring, which enhances exercise supervision for dialysis patients. The system enables healthcare providers to track heart rate variability, muscle fatigue, and caloric expenditure in real time, allowing for personalized exercise adjustments. The dual-network storage feature improves data reliability, allowing remote and offline access to exercise records. Additionally, the caloric expenditure estimation model, based on MET values, provides individualized exercise recommendations tailored to the patient's physical condition.

These findings suggest that this system has significant potential for broader clinical adoption, particularly in healthcare facilities integrating IoT-based monitoring for intradialysis therapy. However, some limitations need to be addressed in future work. The ECG signal occasionally exhibited baseline drift, requiring additional filtering techniques to improve signal stability. Furthermore, expanding the system’s adaptability to other exercise modalities and incorporating AI-driven predictive analytics could further enhance its applicability. Future research should focus on refining the real-time feedback mechanism to optimize exercise safety and efficacy for dialysis patients.

4.3 Limitations and future work

This study has several limitations. First, the proof-of-concept nature and small sample size (n=3) preclude broad statistical conclusions about the system's effectiveness across the diverse hemodialysis population. Future work must include large-scale clinical trials involving a substantial cohort of CKD patients to establish clinical efficacy and reliability. Second, despite filtering, the ECG signal occasionally exhibited baseline drift, indicating a need for advanced signal-processing algorithms. Future iterations could incorporate adaptive filtering or machine learning for improved signal stability. Third, expanding the system's adaptability to other intradialytic exercise modalities (e.g., resistance training) and integrating AI-driven predictive analytics for early anomaly detection would significantly enhance its clinical utility and scope.

5. CONCLUSION

This study successfully developed a real-time IoT-based health monitoring system for intradialysis exercise, integrating multiple biomedical sensors to track heart rate, oxygen saturation, pedal rotations, and leg muscle activity. By combining real-time physiological data with user input, the system enables accurate estimation of caloric expenditure using a MET-based approach, providing a comprehensive assessment of patient exercise performance.

Experimental results demonstrated that the system effectively captured physiological responses across different age groups and health conditions. Younger, healthy respondents exhibited higher cardiovascular and muscular performance, whereas the respondent with chronic kidney disease displayed reduced exercise capacity. These findings validate the system's ability to assess individualized exercise performance and highlight its potential to support medical professionals in optimizing intradialysis training regimens.

The real-time, multi-parameter monitoring capability of this system directly addresses a key gap identified in the literature. For instance, Ribeiro et al. [35] highlighted, in a scoping review, the lack of objective intensity monitoring in current intradialytic exercise prescriptions. Our system, by providing simultaneous, quantifiable data on cadence (via Hall sensor), cardiovascular response (HR, SpO_2), and muscle activity, offers a concrete solution to this need, enabling dose-controlled exercise. Furthermore, while other IoT solutions for general telehealth exist [36], they often focus on monitoring vital signs outside the context of physical activity. The core innovation of our system is its direct integration into the exercise modality for concurrent performance and safety monitoring, a feature crucial for the hemodynamically vulnerable intradialysis period.

Compared to existing monitoring systems, the proposed solution offers key advancements, including dual-network data storage for reliable real-time monitoring, multi-sensor integration for comprehensive physiological tracking, and personalized exercise assessment tailored to patient conditions. These innovations address critical gaps in intradialysis exercise supervision, providing a scalable solution for nephrology care.

Future research should focus on enhancing ECG signal stability, expanding compatibility with various exercise modalities, and incorporating AI-driven predictive analytics for personalized health monitoring. With continued development, this system has the potential to improve patient rehabilitation, enhance safety during intradialysis exercise, and contribute to broader clinical applications in remote health monitoring.

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