Design, Implementation, and Validation of a Low-Cost, Passive RFID Ambulation Tracking System for Postoperative Care

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Structured Abstract—Early and consistent ambulation is a critical indicator of postoperative recovery, closely linked to reduced complications, shorter hospital stays, and improved functional outcomes[1][2]. However, current ambulation tracking methods in hospitals remain limited by manual documentation, inconsistent reporting, and the absence of scalable, automated systems[5][6]. This paper presents the design and evaluation of a low-cost, passive RFID-based infrastructure for monitoring patient ambulation in hospital wards with minimal clinician intervention. The system utilizes passive UHF RFID wristbands and a network of fixed-location RFID readers to detect patient ambulation distance through hallway intersections. Detection data is transmitted to a cloud backend built on Google Firebase, where walking distances and lap counts are captured using spatial path reconstruction algorithms.Controlled static range tests demonstrated reliable tag detection under hospital corridor conditions, with optimal performance observed when a ¼-inch foam backing was used to extend read range and enabling more flexible reader placement. Interviews with a clinical design partner confirmed that the system met core criteria for feasibility, integration, and cost. The ambulation tracking system lays a foundation for future extensions, including in-room detection, integration with electronic health records, and motivational interfaces that incorporate gamification and feedback mechanisms. This work contributes a practical, scalable solution to address the gap in continuous ambulation tracking for postoperative patients, particularly in high-acuity wards where nurse-to-patient ratios limit staff availability.

***Index Terms*—**Ambulation tracking, Hospital mobility, Passive RFID, Postoperative recovery, Wearables

***Clinical and Translational Impact Statement*—**This Early/Pre-Clinical Research demonstrates a low-cost, passive RFID system for hospital ambulation tracking, enabling scalable mobility monitoring to improve postoperative recovery and reduce complications in clinical care.

I. Introduction

Ambulation is a common and practical measure of postoperative recovery, widely prioritized in clinical settings due to its strong association with shorter hospital stays, reduced complications, and improved patient outcomes, including independence, pre-injury status recovery, and discharge readiness [1][2]. As a specific form of mobility, ambulation reflects a patient's broader ability to move and control body position, making it an essential component within the overall assessment of mobility status[3]. For example, reduced rates of ambulation are associated with higher rates of postoperative complications and readmissions. In a cohort study of 128 elective inpatient patients who underwent abdominal surgery, those who did not regain at least 50% of their preoperative ambulation levels within 28 days post-surgery exhibited significantly higher complication rates (16% vs. 1%) and readmission rates (28% vs. 5%) [4]. Findings like these underscore the critical role of early and consistent ambulation in improving postoperative outcomes and highlight the need for reliable methods to monitor and support patient mobility during recovery.

Despite the well-documented benefits of ambulation, there exist limitations in the accuracy and reliability of how it is measured in hospital patients. Current methods for tracking ambulation in clinical settings often rely on patients' self-reported measures, which can yield mixed results and usually prove inaccurate due to recall bias, subjective interpretation, and the lack of continuous, quantitative data needed to track progress effectively [5] [6]. To objectively measure this aspect of mobility,

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assessment tools such as the Highest Level of Mobility (HLM) scale categorize patient ambulation by specific distance milestones, with the highest level representing walking more than 76.2 m [7]. Although useful, the HLM scale is manually recorded by clinical staff based on direct observation, typically twice daily, as there is currently no standardized automated method for capturing this data in routine hospital care[8]. As highlighted by Park et al. (2023), this practice is subject to inherent bias regarding which mobility sessions are documented and how frequently, resulting in inconsistencies and gaps in documentation since continuous, objective measures are not routinely used [9]. Moreover, while the Six-Minute Walk Test (6MWT) and Ten-Meter Walk Test (10MWT) provide standardized ways to measure walking distance and speed, these tests are one-time assessments conducted in controlled conditions rather than continuous, real-time tracking methods [10] [11]. Together, these limitations highlight the need for continuous, low-burden ambulation tracking solutions that can provide more consistent and objective insights into patient mobility in real-world hospital settings.

This need has led to a growing body of clinical research exploring the use of wearable ambulation trackers (e.g., TracPatch, Fitbits, Apple Watches) to quantify ambulation data [12]. These technologies provide more accurate and precise activity metrics such as activity type, frequency, duration, patient exertion, gait, balance, and speed which are crucial factors for assessing ambulation. Although accurate and reliable, these solutions typically incur high per-patient costs (>= USD$ 20), featuring complex, yet sometimes unnecessary, electronic interfaces and components. Wearable devices also possibly raise the need for consistent intervention from hospital staff for charging, cleaning, and data gathering that can pose subsequent operational costs in large-scale deployment. Healthcare providers often encounter barriers like inadequate staffing and high patient acuity, which limit their ability to assist and encourage patient mobility consistently. These limitations highlight the need for scalable, low-burden alternatives that minimize cost and clinician workload while still delivering actionable ambulation data.

While ambulation tracking devices effectively monitor physical activity, they also lack integrated features that actively encourage or motivate patients to increase their mobility. This highlights an opportunity for solutions that go beyond passive monitoring to actively engage and support patients in their recovery journeys [13][14]. A 2025 randomized trial found that gamified text message programs, combined with social support partners, improved adherence to mobility goals among older adults after surgery, although full results are still pending [15]. Similarly, in rehabilitation contexts, gamified balance exercises resulted in 23% higher enjoyment and persistence compared to conventional methods among elderly patients [16]. In clinical practice, hospitals often use whiteboard reminders, progress charts, and motivational notes in patient rooms or unit hallways to encourage ambulation [17]. According to interviews conducted by the authors with clinical design partners, these tools are sometimes paired with anonymous competition between patients, creating a gamified environment that helps motivate individuals coping with both physical and emotional recovery after surgery. These examples suggest that integrating motivational elements, such as gamification and social feedback, into ambulation tracking systems holds promise for improving patient engagement and recovery outcomes.

Altogether, there is a clear need to develop a low-cost system for ambulation tracking that collects ambulation data from post-operative patients in general medical-surgical wards with high nurse-to-patient ratios. Using this data, patients can be motivated to walk more, and healthcare teams can provide timely support, thereby reducing hospital stays, complications, and costs for both patients and hospitals. Based on the literature review presented earlier, existing solutions, while accurate, are often costly, complex, and operationally burdensome at scale. To address these gaps, the proposed system is designed to fulfill several key functional requirements: it must be low-cost (< USD $20) and track core metrics such as distance traveled, time, and laps; and ensure ease of use via a single-use, passive design that eliminates the need for charging or sterilization. It should also provide real-time encouragement through feedback mechanisms, and support secure online data storage for potential integration with hospital records. This paper presents the development of a proof-of-concept RFID hospital ward infrastructure that passively measures distance ambulated with limited clinician intervention. The design establishes a foundation for future integration of motivational features, such as gamification and user progress dashboards, to foster a more engaging and supportive ambulation experience.

II. System Architecture and Design

The ambulation tracking system developed is a modular, RFID-based platform designed to passively monitor patient mobility within hospital wards. It combines a distributed network of fixed-location sensor nodes with passive UHF RFID wristbands worn by patients to detect and record movement through predefined hallway zones. The following sections describe its hardware and software system architectures.

During the early design phase, multiple sensing modalities were considered, including computer vision-based hallway monitoring systems and custom low-cost active wearables similar to commercial fitness trackers. A comparative evaluation using a Pugh chart, developed in collaboration with clinical partners, assessed each option across key criteria such as scalability, privacy, accuracy, maintenance burden, and cost. While computer vision offered high fidelity, it posed significant challenges related to privacy, occlusion, and infrastructural requirements. Active wearables introduced concerns around charging, patient adherence, and data transmission. Ultimately, the passive RFID solution emerged as the most effective and practical approach, satisfying the majority of functional requirements while minimizing cost and complexity in high-acuity care environments.

A. *Hardware System Architecture*

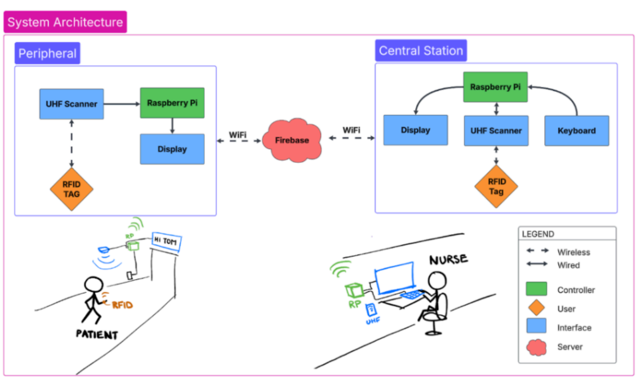

Fig. 1 Overview of the hardware system architecture. "Peripheral" describes the hardware used in each sensor node, which includes a display for the patient interface. "Central Station" is the centralized access point for staff to access and configure the tracking information.

Fig. 1 describes the hardware system architecture within the ward. The ambulation tracking system relies on a distributed network of passive UHF RFID wristbands and fixed-location sensor nodes to enable passive patient ambulation tracking within hospital wards. Each patient is assigned a passive UHF RFID tag embedded into their hospital wristband upon admission. These tags are battery-free, single-use, and designed for minimal interference with daily patient care.

Fig. 2 Left: Ambulation station setup with external antenna on stand. Right: Hardware setup with M7E Hecto RFID reader, Raspberry Pi 5, and Pico microcontroller bridged to the Pi

Fig. 2 showcases the actual hardware setup. Stand-mounted sensor nodes, comprising a Raspberry Pi 5, a Pico microcontroller (bridged to the Raspberry Pi 5 due to the M7E's library requirements), and a SparkFun M7E Hecto RFID reader with an external circularly polarized antenna, are installed at key locations such as hallway intersections and ward entrances. During operation, these nodes detect the presence of RFID wristbands within a typical read range of 2.4 m to 12.1 m, capturing both the detection time and tag ID. This information is transmitted to a cloud backend over Wi-Fi. Each sensor node is mapped to a fixed spatial coordinate, allowing the backend system to infer walking distances between sequential detections. Display screens positioned at nursing stations or along hallway walls provide patients with real-time feedback, including lap counts and motivational dashboard to encourage mobility. The RFID system is modular and adaptable to various ward layouts.

B. *Software System Architecture*

The RFID hardware system is supported by a unified, cloud-based backend that facilitates data ingestion, processing, storage, and visualization. Sensor nodes transmit detection events via HTTPS to serverless endpoints hosted on Google Cloud Functions. Each event is authenticated using pre-shared API keys and logged in Firestore, a HIPAA-eligible, encrypted at rest NoSQL database. Records contain the RFID tag identifier, timestamp, sensor ID, and supporting metadata for analysis.

Backend logic reconstructs patient ambulation paths by analyzing sequences of detections. Each node is mapped with a known (x, y) coordinate, and distances are estimated using predefined floor plan graphs and pathfinding algorithms. Metrics such as total walking distance, lap count, and time-stamped movement trends are computed per patient and stored in Firestore.

User authentication and access control are managed through Firebase Authentication, using institutional Google accounts to ensure secure login. Role-based access limits patient data visibility to authorized clinicians and administrators, with permissions enforced on both the frontend and backend. The application interfaces are hosted on Firebase Hosting and built using HTML, JavaScript, and CSS. Real-time updates are powered by Firestore's synchronization engine.

Two main interfaces facilitate interaction: (1) a ward dashboard displaying anonymized ambulation data to motivate patients collectively, (2) a staff portal for enrolling patients, assigning wristbands, and monitoring progress.

III. METHODOLOGY

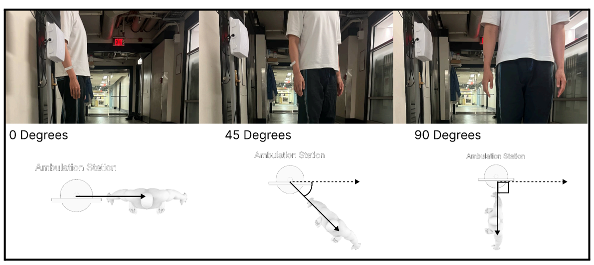

Fig. 3 Diagram describing angle of participant relative to reader for testing

To evaluate the detection performance of the passive RFID ambulation tracking system, we conducted a series of controlled static range tests to simulate real-world hospital deployment conditions. In these tests, a participant wore a wristband embedded with a passive UHF RFID tag, with the arm held still at approximately 1.2 meters above the ground to mimic walking posture. A circularly polarized antenna connected to an RFID reader was mounted on a wall at a matching height. The tests varied two main parameters: the distance between the tag and the reader (ranging from .3 to 6 m, depending on material conditions) and the angle of the participant relative to the reader—either 0 degrees (side-facing), 45 degrees (angled), or 90 degrees (head-on). To understand how material interference might affect detection, tests were conducted under two conditions: one where the tag was exposed on bare skin, and another where a ¼-inch thick foam sheet was placed between the tag and the reader to simulate clothing or padding. For each combination of angle and distance, we recorded whether a detection occurred and noted the corresponding received signal strength indicator (RSSI). These static tests were designed to characterize how tag orientation, distance, and environmental interference affect the reliability of RFID detection in a hospital ward setting. Figure 3 details the testing setup and Figure 4 describes the RFID tag on skin and with a polyurethane foam backing. Additionally, interviews with our clinical design partner were conducted to validate the functional requirements of the system and ensure alignment with real-world clinical workflows.

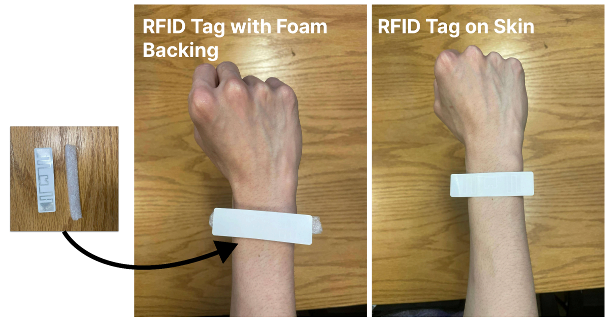

Fig. 4 Left: RFID tag on skin. Right: RFID tag on foam backing.

IV. RESULTS

The static range tests revealed several key trends regarding the detection reliability of passive UHF RFID tags under different angles, distances, and material conditions.

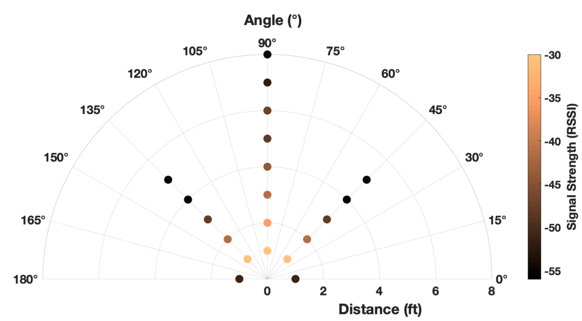

Fig 5. Plot of RSSI values aligned with distance and angle data for bare skin range test.

As seen in Figure 5, when worn directly on skin, tag detection was most reliable at 90° (i.e., head-on to the reader), with consistent detections recorded from .3 to 2.4 m and a maximum RSSI of 55. At 45°, tags were detectable up to 1.5 m, but signal strength dropped off sharply beyond that, with no detections observed at 1.8 m or farther. Detection at 0° (side-facing) was highly limited, with a successful read only at .3 m (1 foot) and signal loss beyond that distance.

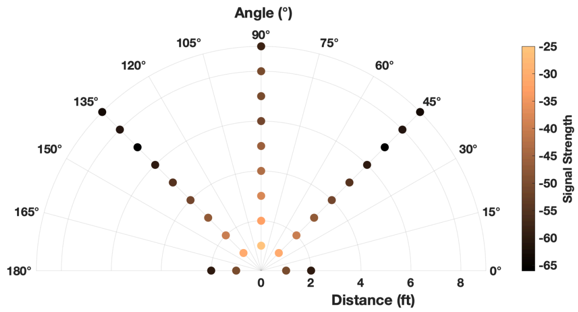

Fig 6. Plot of RSSI values aligned with distance and angle data for foam backing range test.

As seen in Figure 6, when a ¼-inch foam layer was introduced between the tag and the body, to reduce effects of the body, the system's detection range was noticeably affected. At 0°, detection was only observed at .3 and .6 m. At 45°, detections were more robust, extending up to 3.6 m, with RSSI values peaking at 60 to 66 between 1.8 m and 3.6 m. The 90° orientation yielded the highest overall detection range under foam conditions, with consistent reads from 1 to 4.5 m and maximum RSSI values reaching 58. However, detection failed at 6 m for all angles, with the exception of a zero signal (interpreted as no read or dropout) in some cases.

Overall, detection was most reliable when the tag faced the reader directly (90°) or at an oblique angle (45°), and performance was significantly reduced at 0°. Foam interference decreased signal strength and range, but did not prevent detection entirely. These results are consistent with findings from prior RFID healthcare deployments, which similarly report optimal tag readability when line-of-sight and orientation are aligned with the reader antenna [18]. However, this study expands on prior work by quantifying the specific impact of bodily interference and mitigation using foam isolation, which has not been widely benchmarked. Overall, these results validate the feasibility of using passive RFID for ambulation tracking within typical hospital corridor dimensions, provided that reader placement and orientation are strategically optimized.

V. Limitations and Future Work

A. Limitations

While this study demonstrates the feasibility of using passive UHF RFID for tracking ambulation in hospital settings, several limitations should be acknowledged. First, the testing was conducted under controlled indoor conditions with a single participant holding a static posture. In real-world hospital environments, factors such as body motion, occlusion by other individuals, and dynamic postures during walking could influence tag readability and signal strength [18]. Second, the study used a limited range of materials (bare skin and ¼ inch foam) to simulate tag interference. In practice, variations in clothing thickness, moisture, or patient body type introduce additional variability in RFID performance. Third, the angle and distance tests were limited to three fixed orientations and predefined increments, which may not fully capture the range of real walking trajectories or wrist orientations during ambulation. Taken together, these limitations suggest that while the system performs well under ideal conditions, further testing in realistic clinical settings is necessary to validate its robustness and generalizability.

Additionally, the evaluation did not include dynamic walking trials or assess system performance in crowded or electromagnetically noisy hospital environments, where interference from medical equipment or wireless devices may affect signal reliability.

Likewise, the system currently estimates ambulation based on detection sequences across fixed RFID reader locations rather than continuous localization or step-level granularity. While suitable for estimating laps or general movement trends, this may limit precision in cases requiring fine-grained gait analysis. Future testing with larger patient cohorts and dynamic motion scenarios will be essential to validate robustness and generalizability.

From a software perspective, while Firebase provides a scalable and HIPAA-aligned backend infrastructure, real-time performance under high-volume conditions (e.g., peak hospital activity or multi-floor deployments) has not yet been fully stress-tested. Moreover, integration with existing hospital systems, such as electronic health records (EHR), remains theoretical and would require additional development and regulatory review.

Finally, the absence of human subject testing means that the system's usability, acceptance, and motivational impact on patients especially with regard to gamification or behavioral nudges have yet to be evaluated.

B. Future Work

Based on interviews with a hospital physical therapist and our design partner physician, several opportunities emerged to extend the system beyond its initial scope. While the current prototype fulfills the requirements for low-cost deployment, effective hallway-range detection, and a user-friendly interface, future development can broaden its clinical impact and patient engagement.

A key area identified by the physical therapist was the need to track ambulation within patient rooms. Many early recovery movements, such as short walks to the bathroom or pacing beside the bed occur outside hallway coverage zones. Future iterations could explore in-room detection using compact RFID readers, BLE anchors, or other short-range sensors to capture this critical but currently unmeasured mobility.

The therapist also noted that non-ambulatory movements, such as sitting up in bed, repositioning, and upper body movements like arm swings, are meaningful for recovery, particularly in the initial postoperative phase. While outside the original functional requirements and system design scope, incorporating low-burden active sensing through accelerometers, gyroscopes and more on the wristbands, while maintaining low cost and ease of use, could be correlated with ambulation metrics to provide total body mobility understanding.

Another limitation raised was the potential for missed detection in patients with minimal mobility. Patients who are just beginning recovery may not walk far enough to pass two RFID stations, resulting in untracked activity. To address this, deploying additional stations at shorter intervals or designing more sensitive configurations could enable tracking of shorter ambulation paths and ensure credit for early efforts.

The physician design partner also identified key opportunities for integration with clinical research workflows. Specifically, linking the system's data pipeline with research platforms like REDCap could facilitate longitudinal studies of mobility recovery, automate data entry, and streamline integration into broader care protocols.

On the clinical operations side, the addition of a notification system for nurses or care associates could further improve adherence. For instance, if a patient has not reached their daily ambulation goal by a specific time, the system could trigger alerts for care staff to offer encouragement or assistance.

Lastly, expanding the system's gamification features was identified as a critical opportunity. While the current system includes lap tracking and dashboard views, future versions could include more engaging elements such as daily challenges, milestone badges, virtual leaderboards, and patient-customized goals, transforming ambulation into a fun and motivating experience.

These extensions align with both clinical and patient needs and offer a roadmap for transforming the system from a passive tracker into a comprehensive, recovery-supportive mobility platform.

VI. Conclusion

This paper presents the design, implementation, and evaluation of a low-cost, passive RFID-based ambulation tracking system tailored for postoperative patients in hospital wards. Recognizing the critical role that early and consistent ambulation plays in improving clinical outcomes, such as reducing complications, shortening hospital stays, and promoting recovery, the system addresses a key gap in current mobility monitoring tools, which often rely on manual documentation, unreliable patient self-reporting or high-cost wearable devices.

The system leverages passive UHF RFID tags embedded in hospital wristbands and a distributed network of fixed-location readers to enable scalable, low-maintenance tracking of hallway ambulation with minimal clinician intervention. Detection range and performance were verified through controlled static testing, confirming reliable signal acquisition within typical hospital corridor conditions. Notably, tags mounted with a ¼-inch foam backing demonstrated the most consistent detection across greater distances and angles, indicating that this configuration not only improves read reliability but also supports more flexible reader placement in real-world deployments.

Importantly, discussions with a design partner physician confirmed that the prototype meets the core baseline requirements for affordability, deployment feasibility, and user interface integration within clinical workflows. Overall, the system demonstrates a viable path forward for continuous, objective, and low-burden ambulation monitoring in real-world hospital environments.

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