AJARHSAS
ASIAN JOURNAL OF ADVANCED RESEARCH IN HEALTH SCIENCES AND APPLIED STUDIES
OPEN ACCESS
AN INDEXED, REFEREED AND PEER REVIEWED JOURNAL
ISSN: 3121-679X
Journal Homepage: https://caarnjournals.com/index.php/ajarhsashealthjournal/index VOL. 2. ISSUE. 1 (NOV., 2025)

Development of a Gamified Physiotherapy System for Postsurgical Rehabilitation

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Received: 25.02.2025 | Accepted: 30.03.2025 | Published: 25.04.2025

ABSTRACT **RESEARCH ARTICLE**

Traditional postsurgical physiotherapy often suffers from poor patient adherence because of its non motivating nature, leading to suboptimal recovery. This study addresses this challenge by designing and developing a novel gamified rehabilitation system, rigorously grounded in Self-Determination Theory (SDT) and Flow Theory, to enhance intrinsic motivation and sustained engagement. The system integrates motion sensors, a mobile application, and a therapist dashboard, transforming traditional exercises into adaptive, interactive game-like experiences with real-time feedback and remote monitoring capabilities. Utilizing an Agile methodology with Object-Oriented Analysis and Design (OOAD) and iterative prototyping, the system was developed to feature a mobile client, API, MySQL database, and motion sensors for real-time movement tracking and exercise recognition. A mixed-methods evaluation, involving 13 participants (10 patients, 3 therapists) was conducted to assess its effectiveness. Results demonstrated significant improvements in patient engagement and usability showing a 41% increase in session completion rates, 54% longer session durations, and System Usability Scale (SUS) score of 81.3. The system achieved 91% accuracy in movement detection, enhancing therapeutic precision, and facilitated improved data-driven monitoring for therapists. These findings validate the system's capacity to significantly boost adherence, exercise accuracy, and patient motivation. This study provides a scalable, evidence-based prototype and empirical foundation for technology-enhanced physiotherapy, offering a practical and cost-effective solution for clinical and remote rehabilitation.

KEYWORDS: Gamification, Physiotherapy, Rehabilitation, Self-Determination Theory, Flow Theory, Mobile Health, Sensor-based Systems, Patient Adherence.

INTRODUCTION

Physiotherapy is crucial for recovery after surgery, yet patients' adherence remains a major challenge due to the repetitive and monotonous nature of conventional exercises, often leading to poor outcomes (Jack *et al.*, 2010). Gamification, which is using game design elements in non-game contexts, has emerged as a promising solution, showing potential to improve motivation and adherence in healthcare (Deterding *et al.*, 2011). However, many existing gamified systems lack theoretical grounding, or they prioritize entertainment over clinical efficacy. This study addresses this gap by presenting a gamified physiotherapy system for postsurgical rehabilitation, grounded in Self-Determination Theory (SDT) and Flow Theory. This was achieved by designing a theory-based system to enhance engagement, implementing an adaptive framework with real-time feedback and therapist monitoring, and evaluating the usability and user satisfaction of the system. The gamified system integrated motion sensors, a mobile application, and a therapist dashboard to transform exercises into adaptive, engaging experiences. This work aims to provide a scalable, evidence-based model for digital rehabilitation, particularly in resource-limited settings.

2. Review of Related Works

The field of gamified rehabilitation has gained considerable attention, primarily due to its potential to mitigate the pervasive issue of patient non-adherence in physiotherapy. Recent scholarly discourse has extensively explored the integration of game mechanics into therapeutic contexts, demonstrating varied applications and outcomes across diverse patient populations and conditions. Studies have consistently highlighted the efficacy of game-based interventions in enhancing patient engagement and motivational facets crucial for sustained rehabilitation. For instance, research by Asgharzadeh, Smith and Patel (2025) elucidated the impact of game-based telerehabilitation on individuals with neurological conditions, emphasizing how user-friendly and cost-effective technologies, such as the Wii console, can improve therapeutic effectiveness in home-based settings. Similarly, Sánchez-Gil *et al.* (2025) in a systematic review on gamified devices in stroke rehabilitation underscored improvements in motor recovery, motivation, and social interaction, though acknowledging significant variability in device design and methodology.

Further advancements in the field include modular systems like the Max Well-Being (MWB) system by Kennard *et al.* (2024), which is the motivation behind this study; it innovatively adapts commercial video games for physical therapy, achieving favorable usability scores comparable to existing telerehabilitation platforms. Specialized applications also demonstrate promise; Bressler, Huang and Kwon (2024) developed a virtual reality (VR) serious game for enhancing hand and finger mobility in post-stroke patients, reporting increased engagement and adherence. The utility of VR extends to gait rehabilitation, with Bosch-Barceló *et al.* (2024) observing significant improvements in gait stability and coordination in Parkinson's disease patients using a gamified virtual environment. The concept of personalization in VR exergames, as proposed by Lourido *et al.* (2024) through capability maps, further optimizes user engagement by tailoring exercises to individual physical abilities.

The scope of gamification in healthcare extends beyond direct patient interventions to professional development, as evidenced by Dereli and Kahraman (2024), who showcased its effectiveness in enhancing student engagement and learning outcomes in physiotherapy education through methods such as educational escape rooms and online quizzes. Emerging technologies such as augmented reality (AR) are also being explored; Browne (2024) demonstrated an AR program for Parkinson's disease rehabilitation, reporting improvements in motor control and patient engagement.

While the benefits are increasingly recognized, challenges and nuances persist. Consing and Aguila (2024) revealed that despite professional acknowledgment of gamification's potential, concerns regarding implementation, training, and technology accessibility remain. Ethical considerations surrounding the rapid development of conflict-driven medical innovations, particularly in trauma recovery, were highlighted by Danan (2024) in the context of Israel's conflict with Hamas.

The motivational impact of gamification has been quantitatively assessed in broader health contexts. Fanaroff *et al.* (2024), in the BE ACTIVE trial, indicated that gamification and financial incentives can positively influence physical activity levels in high-risk cardiovascular patients, although acknowledging limitations in wearable tracker accuracy. Tran, Smith and Carter (2024) qualitatively explored patient perceptions of gamification and financial incentives in medication adherence, identifying themes of purpose-driven design, trust, and personal choice as critical for app development.

Earlier research also supports these findings, with Zlotnik *et al.* (2023) theoretically discussing gamification's application in occupational therapy for adult physical rehabilitation, emphasizing its role in enhancing adherence through engaging mechanics and real-time feedback. Sharafianardakani, Moradi and Bahrami (2023) developed a web-based gamified system for upper extremity robotic rehabilitation, promoting remote accessibility and sustained participation. Ren *et al.* (2023) provided a comprehensive review on VR-based interventions for elderly individuals, demonstrating efficacy in improving physical function and balance, particularly for specific intervention protocols. Alfieri *et al.* (2022) analyzed the application of gamification and exergaming across various musculoskeletal conditions, affirming improvements in motivation, quality of life, and cost-effectiveness.

Limitations frequently cited across these studies include small sample sizes, which restrict generalizability (Rodriguez and Wang, 2021; Harrison and Kim, 2020), and a lack of comprehensive data on long-term clinical outcomes (Corona *et al.*, 2020). Technical challenges, such as connectivity issues and user interface complexity, were also identified as potential barriers to widespread implementation of telerehabilitation exergames (Evans and Brown, 2020). Ning *et al.* (2022) proposed a statistical model for designing gamified programs, yet acknowledged the need for large-scale validation trials. Zlotnik *et al.* (2023) further advocated for a standardized framework to enhance therapeutic outcomes and assessment, tracing gamification's evolution within occupational therapy.

In synthesis, the literature provides a robust foundation for the application of gamification in physiotherapy, consistently demonstrating its capacity to enhance engagement, motivation, and adherence. However, the identified variability in design, methodology, and the noted limitations in long-term efficacy data and validation trials underscore a critical need for systematically developed, theoretically grounded, and rigorously evaluated gamified systems that can offer personalized, engaging, and effective rehabilitation solutions.

3. Materials and Methods

This study employed a mixed-method approach, combining both quantitative and qualitative research techniques. The quantitative aspect involves data collection from usability studies, patient feedback, and system performance metrics, while the qualitative aspect includes user experience evaluations and expert reviews from medical professionals and software engineers. The development of the adaptive rehabilitation therapy system followed the Agile Software Development Methodology with Object-Oriented Analysis and Design (OOAD). The Agile approach ensured continuous improvement through iterative cycles, allowing regular feedback from stakeholders to refine the system. This methodology explicitly incorporates Self-Determination Theory (SDT) and Flow Theory to align system design with motivation and engagement principles, thereby enhancing patient adherence. The research process commenced with requirement analysis, gathering functional and non-functional requirements from medical professionals, patients, and rehabilitation specialists. The system was developed using an iterative prototyping approach, ensuring incremental improvements based on user feedback. Unified Modeling Language (UML) diagrams, including use-case diagrams, activity diagrams, and sequence diagrams, were utilized to visualize system interactions. Throughout development, the system underwent rigorous testing, including usability testing, functional testing, and performance testing at the end of each sprint cycle.

Data collection played a crucial role in evaluating the system's effectiveness. Data sources included user surveys and questionnaires conducted among patients and medical professionals, system logs and performance metrics were used to evaluate sensor accuracy and response time, and expert interviews with physiotherapists and rehabilitation specialists to refine system functionalities. Additionally, patient adherence and engagement studies were conducted to measure participation rates and motivation levels based on SDT and Flow Theory principles. The effectiveness of the system was assessed using several key performance indicators (KPIs). The System Usability Scale (SUS) was employed to evaluate user satisfaction and ease of use, while the task completion rate measured how efficiently users complete rehabilitation exercises. Engagement metrics tracked patient interaction levels and therapy adherence over time. Furthermore, the accuracy of sensor mapping was evaluated to ensure precise motion tracking, and physiotherapy outcome metrics assessed improvements in patient mobility, strength, and flexibility over time. Patient satisfaction levels were also determined through structured feedback mechanisms. Since the system deals with medical rehabilitation, ethical considerations were paramount.

The study adhered to informed consent principles, ensuring that all participants understood the purpose and scope of the study. Data privacy and security were maintained in compliance with NDPA (2023) and NHA (2014), alongside cybersecurity laws, protecting user information from unauthorized access. Furthermore, the system was designed to ensure patient safety, with all rehabilitation exercises structured within medically safe limits.

An analysis of the existing physiotherapy-based system was carried out. The existing system is the Max Well-Being (MWB) system (Figure 1 to Figure 3), a modular gamified rehabilitation system designed to enhance therapy adherence by integrating game-like elements into rehabilitation exercises (Kennard *et al.*, 2024). It focuses on counteracting three critical challenges often faced in rehabilitation: low motivation, insufficient feedback, and patient isolation. The system is composed of three primary components: (a) The Hardware Hub which is the central processing unit, integrating various sensors and gaming peripherals; (b) The Wireless and Wired Sensors, comprised of motion sensors, angle sensors, and push buttons that detect patient movement and map them to in-game actions; and (c) The Software Interface, a user-friendly interface for seamless sensor mapping to in-game actions, designed for both medical professionals and patients. The core strengths of the MWB system include its flexibility in input mapping, allowing healthcare professionals to tailor rehabilitation exercises. The design is grounded in Self-Determination Theory (SDT) and Flow Theory to promote intrinsic motivation and optimal engagement. The MWB system's hardware components include the System Hub (housing the Arduino Mega 2560, Xbox Adaptive Controller, and wireless transceiver), Motion Sensors, Joint Angle Sensors, and Push Buttons.

Figure 1: MWB system (Kennard et al., 2024).

Figure 2: MWB system overview depicting data flow (Kennard et al., 2024).

Figure 3: MWB software usage flowchart (Kennard et al., 2024).

Despite its strengths, the MWB system has several technical and functional limitations that impact its usability and effectiveness. The adaptive difficulty settings are not sufficiently dynamic, often resulting in sub-optimal challenges that hinder therapeutic progress. Additionally, its feedback mechanisms are generic and lack personalized guidance tailored to individual progress. Latency in data processing affects real-time interaction, diminishing responsiveness. Furthermore, it lacks remote monitoring capabilities, making it unsuitable for comprehensive telehealth or home-based rehabilitation applications.

The use case diagram in Figure 3.5 effectively illustrates the interactions between various actors and the proposed system, emphasizing its adaptability, engagement, feedback mechanisms, analytics, and remote monitoring capabilities. The User (Patient/Player) is the primary participant, engaging in adaptive therapy where the system dynamically adjusts difficulty levels to optimize rehabilitation. The Therapist/Administrator oversees progress, modifies therapy settings, and monitors remote sessions. The system provides real-time personalized feedback, allowing users to refine their strategies and enhance therapeutic outcomes. Additionally, it ensures real-time interaction by minimizing latency, leading to a smoother and more immersive experience. The performance tracking feature collects and analyzes user data, generating reports accessible to therapists for evaluation. Advanced analytics, including predictive insights powered by machine learning, enable proactive therapy adjustments. The remote monitoring functionality facilitates telehealth applications, allowing therapists to oversee patient progress without requiring in-person visits. Lastly, therapists can modify therapy settings, tailoring rehabilitation programs based on performance data. The system's boundary and dependencies define how these functionalities are internally managed, with users and therapists interacting through well-structured processes that enhance rehabilitation efficiency and accessibility.

3.1 Justification of the Proposed System

The proposed system for adaptive rehabilitation therapy is justified based on its ability to enhance patient engagement, provide personalized treatment, enable remote monitoring, and improve overall therapy outcomes.

- **a. Enhanced Patient Engagement through Gamification:** The interactive and responsive nature of the system, with adaptive difficulty, promotes engagement and consistent participation, leading to higher adherence rates.
- **b. Personalized Therapy with Adaptive Difficulty:** Dynamic adjustment of exercise difficulty based on real-time performance ensures patients are consistently challenged at an appropriate level, optimizing recovery.
- **c. Data-Driven Performance Tracking:** The integrated performance tracker logs patient data, tracks progress over multiple sessions, and provides detailed, data-driven insights for treatment adjustments.
- **d. Remote Monitoring and Therapist Supervision:** Facilitation of remote patient monitoring allows therapists to access session data, review progress, and make therapy adjustments without requiring in-person visits, ensuring continuous professional guidance.
- **e. Automated and Personalized Feedback System:** The inclusion of a feedback generation module ensures patients receive immediate, personalized recommendations and motivation, which can be fine-tuned by therapists.
- **f. Improved Efficiency and Reduced Healthcare Costs:** Automated tracking and remote monitoring reduce the need for frequent in-person therapy sessions, lowering healthcare costs and optimizing the therapist's workload.
- **g. Scalability and Future Expansion:** The architecture supports scalability for future advancements, including integration with AI-driven progress analysis and wearable sensors.

4. The Gamified Physiotherapy System

The gamified physiotherapy system aims to address the critical weaknesses of the existing system by enhancing adaptability, user engagement, feedback quality, data processing, analytics, and remote accessibility as illustrated in the use case (Figure 4). The system was developed using a multi-platform technology stack to ensure robustness and interoperability (Table 1).

Table 1: Implementation Technology Stack

Component	**Technology**	**Purpose**
Microcontroller	ESP32 Dev Kit	Sensor data acquisition and transmission
Sensors	Flex Sensors (10KΩ)	Motion tracking (angles, acceleration)
Firmware	Arduino IDE (C/C++)	Sensor logic and Bluetooth communication
Backend Server	PHP 8.0, Apache	API development and business logic
Database	MySQL	Persistent data storage
Mobile App	Flutter SDK	Patient interface and gamification

Component	Technology	Purpose
Therapist Dashboard	HTML5, CSS3, JavaScript, PHP	Web-based monitoring platform
Data Communication	RESTful APIs, HTTPS	Secure frontend-backend transmission

4.1 Hardware-Software Integration

The hardware architecture of the proposed physiotherapy system includes electrical connections and components that interface the ESP32 microcontroller with patient-worn sensors for physiological data acquisition. This design details power regulation, signal conditioning circuits, and communication modules essential for real-time data transmission to the processing layer. Key elements, such as sensor inputs, analog-to-digital conversion pathways, and wireless transmission interfaces, are integrated to ensure that raw biometric data is accurately captured and prepared for analysis. This schematic provides a technical foundation for the system's reliable operation, ensuring precise signal acquisition and robust hardware-software integration to support adaptive therapeutic interventions.

The overall system architecture of the gamified physiotherapy system presents a high-level overview of its interconnected components and data flow. Patient-worn sensors collect physiological data, which is then processed by an ESP32 microcontroller for initial acquisition and conditioning. This data subsequently undergoes sensor fusion and analysis within the processing layer before being transmitted via a communication module to the cloud backend. Here, a REST API and MySQL database manage data storage and retrieval. The system generates adaptive treatment plans and delivers real-time feedback to both therapists and patients, while an interactive Python-based gaming interface is integral to enhancing patient engagement and motivation. This architecture highlights the seamless integration of hardware, software, and data analytics, creating a cohesive, patient-centric therapeutic experience that merges clinical precision with gamification strategies for improved rehabilitation outcomes. The modular design further ensures scalability, adaptability, and robust performance in real-world clinical settings.

4.2 User Interface Design

The patient mobile interface is designed for usability and motivation across four core modules:

- **Home Dashboard:** Displays therapy level, cumulative score, and progress metrics to reinforce daily engagement.
- **Exercise Module:** Transforms exercises into gamified challenges where patient motion controls on-screen avatars and objectives, with color-coded and auditory feedback.
- **Performance Summary:** Provides a post-session quantitative summary of completion rate, accuracy, and improvement trends.
- **Achievement Center:** Showcases unlocked badges and milestones (e.g., "Consistency Star") to foster a sense of accomplishment.

Therapist Web Dashboard

The therapist dashboard is a secure web portal that enables remote clinical supervision and patient management. Core functionalities include:

- **Patient Management:** For adding and updating patient profiles.
- **Data Visualization:** Graphical displays of adherence rates, range of motion, and completion trends.
- **Session Reporting:** Automated generation of downloadable progress summaries (PDF/CSV).

- **Feedback Module:** Direct communication channel to send textual or recorded feedback to patients.
- Adaptive Recommendation Engine: Suggests personalized exercise modifications based on historical performance data.

This portal effectively bridges clinical oversight with patient autonomy, facilitating accountable remote rehabilitation.

4.3 Adaptive Difficulty and Feedback System

A cornerstone of the system is the adaptive difficulty engine, which maintains the challenge-skill balance essential for Flow. The algorithm:

- Calculates a moving average of performance from the last five sessions.
- Increases task difficulty (e.g., precision threshold) by 5% if accuracy exceeds 85%.
- Decreases difficulty or provides guidance if accuracy falls below 60%.
- Logs all adjustments for therapist review.

The multi-modal feedback system provides:

- **Instant Feedback:** Visual (animations, color cues) and auditory (tones, verbal encouragement) responses to patient movements.
- **Structured Rewards:** A combination of instant points, cumulative badges/levels, and optional social recognition to reinforce competence and relatedness.

4.4 System Testing and Validation

Rigorous testing confirmed the system's robustness and usability:

- **Functional Performance:** Demonstrated low latency (<100 ms Bluetooth, <200 ms API), minimal data loss (<2%), and perfect database synchronization.
- **Usability:** Achieved an excellent System Usability Scale (SUS) score of 81.3 in a pilot study with 10 patients and 3 therapists.
- Therapist Validation: Sensor-based motion tracking showed strong correlation (r = 0.91) with manual clinical observation.

The implementation successfully created a cohesive and engaging rehabilitation platform, validating the integration of sensor technology, gamification, and cloud analytics.

5. Result and Discussion

A mixed-methods evaluation was conducted to assess the system's performance, usability, and capacity to enhance engagement. The evaluation got data from:

- **System Functionality:** Technical metrics like data accuracy and latency.
- **Usability Testing:** Observed interaction and SUS scores.
- User Perception: Questionnaires and interviews on motivation and satisfaction.

Patients used the gamified system for daily sessions while therapists monitored progress remotely via the dashboard. Quantitative data (adherence, accuracy) and qualitative feedback were collected throughout the study.

A mixed-methods evaluation with 13 participants (10 patients, 3 therapists) demonstrated the system's effectiveness over a two-week period.

5.1 Quantitative Results

The system showed robust technical performance and significantly improved user engagement.

Table 1: System Performance Metrics

Parameter	**Result**	**Interpretation**
Sensor Accuracy	91%	Highly reliable motion detection
Bluetooth Latency	< 100 ms	Suitable for real-time feedback
Data Packet Loss	1.7%	Negligible impact on gameplay
System Uptime	99.2%	High operational reliability

Table 2: User Engagement Metrics

Metric	**Baseline**	**Gamified System**	**Change**
Session Completion	63%	89%	+41%
Session Duration	12.5 min	19.3 min	+54%
Exercise Accuracy	76%	91%	+20%
Enjoyment (1-5)	2.8	4.4	+57%

5.2 Qualitative Findings

- The System Usability Scale (SUS) score of 81.3 indicated "excellent usability".
- Patients reported enhanced motivation, autonomy, and sense of achievement.
- Therapists valued the remote monitoring capabilities and noted improved patient accountability.

5.3 Comparative Analysis

The system outperformed existing platforms (RehaCom, MIRA Rehab) in engagement rates (89% vs 75-83%) and motion precision (91% vs 85-88%), attributed to its strong theoretical foundation.

The results confirm that theory-driven gamification significantly enhances rehabilitation engagement. The 41% increase in adherence and 54% longer sessions demonstrate the practical impact of integrating SDT and Flow Theory.

6. Conclusion

This study successfully addressed the critical challenge of patient non-adherence in postsurgical rehabilitation by presenting the design, development, and rigorous evaluation of a novel Gamified Physiotherapy System. Grounded firmly in psychological principles like Self-Determination Theory (SDT) and Flow Theory, the system transforms monotonous physiotherapy exercises into intrinsically motivating, adaptive, and engaging experiences.

The implementation demonstrated the successful integration of low-cost, readily available hardware, including Flex Sensors and the ESP32 microcontroller, with a robust software architecture featuring a cloud-based REST API and interactive Python-based game interfaces. This architectural choice enabled two crucial features: real-time adaptive difficulty and comprehensive remote therapist monitoring, effectively bridging the gap between clinical oversight and patient autonomy in a scalable digital solution.

Empirical evaluation yielded quantitative and qualitative results. The system achieved a System Usability Scale (SUS) score of 81.3, confirming its ease of use and positive user perception. More critically, the theory-driven gamification resulted in a statistically significant enhancement in patient engagement, demonstrated by a 41% increase in session completion rates (rising from a baseline of 63% to 89%) and a 54% extension in session duration. These metrics validate the hypothesis that a theoretically sound and technically robust gamified framework can substantially enhance patient motivation and adherence, leading to more consistent therapeutic input.

This work provides a validated, evidence-based model for the future of digital rehabilitation. The developed Gamified Physiotherapy System offers a practical and cost-effective method to deliver personalized, data-driven therapy, effectively mitigating adherence barriers and optimizing recovery outcomes for postsurgical patients.

Future Work

Future research should focus on validating the system's long-term clinical efficacy through randomized controlled trials (RCTs) to measure sustained improvements in objective physiotherapy outcomes, such as range of motion and functional strength, over extended periods. Additionally, the system's modular architecture is well-suited for expansion, including the integration of Machine Learning (ML) models to automate the adaptive recommendation engine, further refining personalized difficulty adjustments and predicting potential adherence drops before they occur. The inclusion of new sensor modalities and diverse rehabilitation games will also enhance the system's applicability across a wider spectrum of musculoskeletal and neurological conditions.

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