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Research Article

Flexi-Heal: Development of a Portable IoT-Based Elbow Rehabilitation Device for Home Therapy

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Abstract: *Stroke commonly results in long-term upper-limb impairment, particularly limited elbow mobility, requiring continuous rehabilitation. However, existing rehabilitation devices are often costly, clinic-based, and inaccessible for regular home use. This study aims to develop a portable, low-cost elbow rehabilitation solution to support home-based therapy. Flexi-Heal is an IoT-enabled device that uses an ESP32 microcontroller and a servo motor to provide controlled elbow flexion with adjustable angles and repetitions, monitored via the Blynk mobile application. The system promotes independent rehabilitation, improves therapy accessibility, and reduces reliance on frequent clinic visits. Overall, Flexi-Heal demonstrates strong potential as an affordable and practical home rehabilitation device.*

1. INTRODUCTION

Innovation in healthcare technology is important for addressing persistent challenges faced by patients, caregivers, and medical professionals, particularly in post-stroke rehabilitation. Stroke is a leading cause of long-term disability worldwide, and upper-limb impairment, especially reduced elbow range of motion, remains one of the most common functional limitations experienced by survivors (Feigin et al., 2021), (Bertani et al., 2017). These impairments significantly affect daily activities such as eating, dressing, and personal hygiene, reducing patient independence and quality of life. Although repetitive and structured physiotherapy is known to promote motor recovery and neuroplasticity, access to continuous rehabilitation remains limited due to cost, transportation barriers, and reliance on clinic-based therapy sessions (Akbari et al., 2021), (Knepley et al., 2021).

Recent advances in rehabilitation engineering have introduced wearable and robotic-assisted devices to support upper-limb recovery. Studies have shown that elbow rehabilitation systems can improve movement consistency and functional outcomes when exercises are performed regularly (Huang et al., 2021), (de la Iglesia et al., 2020). However, many existing solutions are designed for clinical use, are costly, or lack portability, making them less suitable for long-term home-based rehabilitation (Langerak et al., 2024), (Salchow-Hömmen et al., 2019). As a result, there is a growing need for affordable and user-friendly rehabilitation devices that allow patients to continue therapy independently outside hospital settings.

This innovation article presents Flexi-Heal, a portable IoT-based elbow rehabilitation device developed to support home-based therapy using a simple and cost-effective design. The concept of Flexi-Heal is shared to demonstrate how accessible electronic components and mobile application integration can be creatively applied to address real rehabilitation challenges. By enabling adjustable elbow movement angles and repetition control, the system encourages consistent exercise while allowing basic monitoring of therapy sessions (Demirsoy et al., 2024), (Iandolo et al., 2020).

Documenting this innovation serves multiple purposes, including knowledge sharing, academic dissemination, and participation in innovation showcases. More importantly, Flexi-Heal is designed to inspire students and early-stage innovators by demonstrating that meaningful healthcare solutions can be achieved without highly complex or expensive systems. The device emphasizes user-centred design, portability, and ease of operation, aligning with current trends in home-based rehabilitation technology (Moskiewicz & Sarzyńska-Długosz, 2025), (Tanaka & Ota, 2020).

Finally, this article provides evidence of the potential impact of Flexi-Heal on the community and healthcare sector. By supporting independent rehabilitation and reducing dependence on frequent clinic visits, the system has the potential to improve therapy adherence and reduce long-term healthcare costs. Flexi-Heal contributes to the broader goal of improving access to rehabilitation services and aligns with global efforts to promote good health and well-being through innovative and inclusive healthcare solutions (WHO, 2019).

2. LITERATURE REVIEW

2.1 UPPER-LIMB REHABILITATION AFTER STROKE

Upper-limb impairment is one of the most common consequences of stroke, with reduced elbow range of motion frequently limiting a patient’s ability to perform daily activities. Research has shown that repetitive and task-oriented exercises are essential to promote motor recovery and neuroplasticity in stroke patients (Feigin et al., 2021), (Bertani et al., 2017). Without regular rehabilitation, muscle stiffness and joint weakness may persist, leading to long-term functional limitations. Conventional rehabilitation typically relies on supervised physiotherapy sessions, which may be difficult for patients to attend consistently due to time, cost, and accessibility constraints (Akbari et al., 2021), (Knepley et al., 2021).

2.2 ROBOTIC AND WEARABLE ELBOW REHABILITATION DEVICES

To address limitations of traditional therapy, researchers have developed robotic and wearable rehabilitation devices for upper-limb recovery. Huang et al. introduced a wearable elbow robot designed to assist elbow movement during rehabilitation, demonstrating improved motion control and user engagement (Huang et al., 2021). Similarly, de la Iglesia et al. developed a connected elbow exoskeleton system integrated with virtual reality, enabling guided exercises and remote monitoring (de la Iglesia et al., 2020). These systems highlight the potential of robotic assistance in improving rehabilitation effectiveness through controlled and repetitive movement.

2.3 IOT-BASED AND HOME REHABILITATION SYSTEMS

Recent studies have focused on IoT-enabled rehabilitation systems that allow patients to perform therapy at home while tracking progress remotely. Demirsoy et al. developed an IoT-based elbow rehabilitation device that records movement data and supports automated training (Demirsoy et al., 2024). Akbari and Haghverd emphasized the importance of home-based rehabilitation systems, particularly during periods when access to clinical therapy is limited (Akbari et al., 2021). These approaches show that IoT technology can improve therapy adherence by enabling flexible, home-based rehabilitation solutions.

2.4 LIMITATIONS OF EXISTING SOLUTIONS

Despite their benefits, many existing robotic and wearable rehabilitation devices are expensive, complex, and designed mainly for clinical environments. Langerak et al. highlighted that home-based rehabilitation devices must be simple, safe, and affordable to be suitable for long-term use (Langerak et al., 2024). Additionally, some systems require advanced sensors or complex calibration, which may not be practical for patients with limited technical knowledge (Salchow-Hömmen et al., 2019), (Iandolo et al., 2020). These limitations reduce the widespread adoption of current rehabilitation technologies, especially among home users.

To summarize and compare the characteristics of existing elbow rehabilitation systems, Table 1 presents a matrix synthesis of selected studies, highlighting the system type, main features, and key limitations. This comparison helps identify common design challenges, particularly related to cost, system complexity, portability, and suitability for home-based use.

Table 1: Matrix Synthesis of Reviewed Work

Author / System	Type of System	Main Features	Limitations
Huang et al. (2021) [5]	Wearable elbow robot	Assisted elbow movement, sensor-based monitoring	Designed mainly for clinical use, limited portability
De la Iglesia et al. (2020) [6]	Elbow exoskeleton with VR	Guided rehabilitation with virtual reality support	High system complexity and cost
Akbari & Haghverd (2021) [7]	Home-based rehab framework	Emphasizes remote therapy and accessibility	Conceptual design, limited physical implementation
Demirsoy et al. (2024) [9]	IoT-based elbow rehab device	Automated elbow movement, IoT data logging	Requires advanced control setup
Tanaka & Ota (2020) [19]	Low-cost motorized therapy device	Affordable design for home rehabilitation	Limited monitoring and user feedback

2.5 MOTIVATION FOR FLEXI-HEAL

Based on the reviewed literature, there is a clear need for a simple, portable, and low-cost elbow rehabilitation device that supports home-based therapy. Flexi-Heal is developed to address this gap by focusing on controlled elbow movement, ease of use, and basic IoT integration without relying on complex or costly components. By enabling adjustable movement angles and repetitions, Flexi-Heal aims to support consistent rehabilitation practice while remaining accessible to a wider group of users. This approach aligns with current research trends emphasizing affordability, portability, and patient-centred rehabilitation design (Demirsoy et al., 2024), (Tanaka & Ota, 2020), (WHO, 2019).

3. METHODOLOGY

The methodology focuses on developing a simple and portable elbow rehabilitation device for home use. Flexi-Heal uses an ESP32 microcontroller to control a high-torque servo motor that assists elbow flexion within a safe range. Users set the movement angle and repetition count through a Wi-Fi–connected mobile application. During operation, the servo repeatedly moves the elbow between the selected angle and the starting position to provide guided rehabilitation exercises. Session data, including angles, repetitions, and duration, are recorded in an online spreadsheet for monitoring. System testing confirmed smooth movement, stable operation, and safe performance during repeated therapy sessions.

3.1 INNOVATION OVERVIEW

The flexi-heal control system employs microcontroller-based architecture, with the ESP32 serving as the main controller. The controller circuit was initially designed and verified using simulation and wiring diagrams to ensure correct component integration. Following validation, the circuit was implemented on a prototype board to achieve a compact and stable configuration. The system integrates the servo motor, power supply, and communication interfaces required to deliver controlled and safe elbow rehabilitation movements.

Figure 1 illustrates the block diagram of the Flexi-Heal portable elbow rehabilitation system, showing the relationship between the input, process, and output components. The system is powered by a Li-Po battery, which supplies energy through an On/Off switch to control system operation. Voltage regulation is achieved using step-down converters to ensure suitable operating levels for the ESP32 microcontroller and peripheral components.

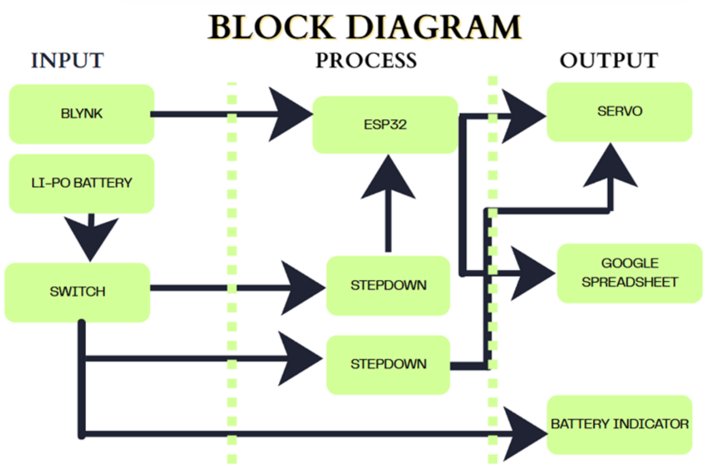

Figure 1: Block Diagram of the System.

The ESP32 functions as the main processing unit, receiving user-defined rehabilitation parameters from the Blynk mobile application via Wi-Fi. Based on these inputs, the controller generates control signals to drive the servo motor, which performs the elbow flexion movements. Rehabilitation session data are transmitted by the ESP32 and stored in a Google Spreadsheet for monitoring and progress tracking. In addition, a battery indicator provides real-time information on power status. This block diagram highlights the integration of power management, control processing, actuation, and IoT-based data monitoring within the Flexi-Heal system.

Figure 2 presents the system flowchart of the Flexi-Heal device, outlining the operational sequence from initialization to the completion of a therapy session. The process begins with the ESP32 establishing a connection to the Blynk application, after which the user selects the target angle and number of repetitions. Based on these inputs, the controller drives the servo motor to execute the prescribed elbow movements while continuously monitoring for stop commands. Upon completion of the set repetitions, the motor is halted and the therapy session is terminated, ensuring structured, controlled, and safe rehabilitation operation.

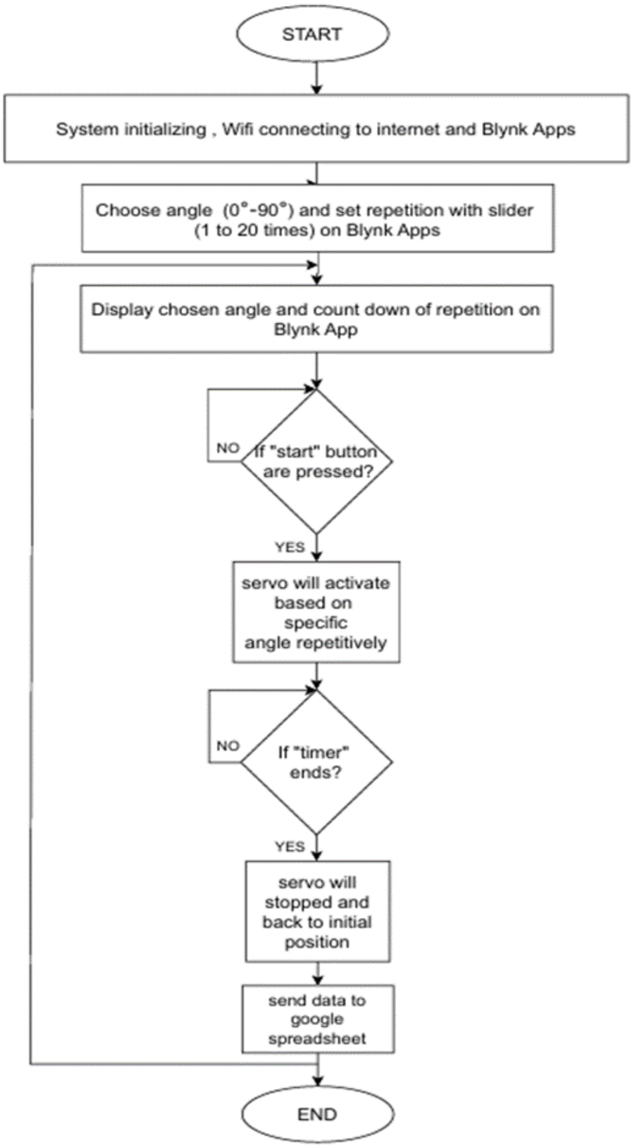

Figure 2: Flow Chart of Operation of the System.

3.2 INNOVATION HARDWARE

The portable elbow rehabilitation system is built around the ESP32 Development Module, which functions as the main controller due to its integrated Wi-Fi capability and seamless integration with the Blynk IoT platform. The ESP32 wirelessly receives user-defined parameters, including target angle and repetition count, and processes these inputs to control the actuator. An 80 kg high-torque servo motor is employed to deliver controlled and repetitive elbow movements suitable for rehabilitation exercises. The system is powered by an 11.1 V, 2200 mAh Li-Po battery, with a step-down voltage regulator ensuring safe operating levels. An On/Off switch is included for user safety and power control. Rehabilitation session data are transmitted via Wi-Fi and stored in Google Spreadsheet, enabling remote monitoring and progress tracking. This compact and portable hardware design supports reliable and home-based elbow rehabilitation.

3.2.1 PROTOTYPE DEVELOPMENT

Figure 3 illustrates the three-dimensional (3D) design of the Flexi-Heal portable elbow rehabilitation device, showing the front and rear views of the prototype enclosure. The design emphasizes portability, user safety, and ease of use, which are essential for home-based rehabilitation applications. The compact enclosure houses all electronic components within a conduction box, protecting the system from external damage while ensuring stable operation during repetitive therapy sessions.

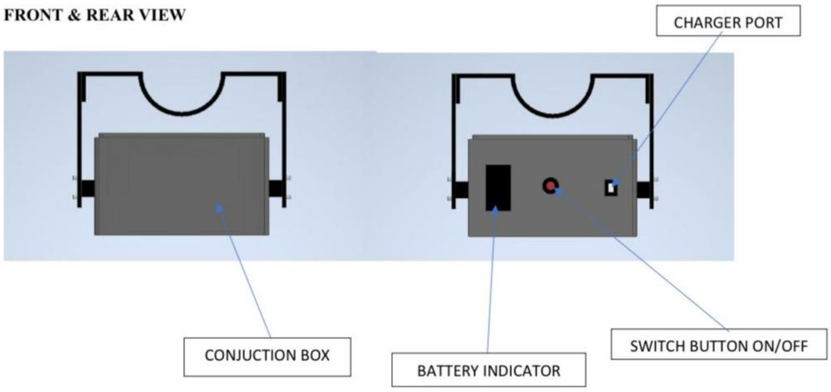

Figure 3 : 3D Design Flexi-Heal Portable Elbow Rehabilitation Device.

From a rehabilitation perspective, the external layout is designed to allow patients or caregivers to operate the device with minimal effort. The On/Off switch enables easy control of therapy sessions, allowing users to start or stop rehabilitation exercises safely. A battery indicator is included to provide clear visual feedback on power status, ensuring that therapy sessions are not interrupted due to insufficient battery charge. The charger port allows convenient recharging of the Li-Po battery, supporting continuous and repeated use at home.

The overall mechanical structure is designed to support controlled elbow movement while maintaining comfort and stability during rehabilitation exercises. By integrating functional controls and power management into a compact and accessible enclosure, the Flexi-Heal prototype supports independent rehabilitation, improves usability for stroke patients, and enhances the practicality of home-based elbow therapy.

4. FINDINGS

This section presents the main findings obtained from the development and testing of the Flexi-Heal Portable Elbow Rehabilitation System. The findings focus on elbow movement performance, rehabilitation progress, system reliability, and the effectiveness of IoT integration for home-based therapy.

4.1 ELBOW MOVEMENT PERFORMANCE

Based on the testing results, the Flexi-Heal system was able to control elbow movement smoothly and consistently within the set rehabilitation range. The device successfully assisted elbow flexion between 0° and 45°, which is suitable for early-stage stroke rehabilitation. The servo motor responded accurately to the angle settings sent from the Blynk application, and no sudden or unstable movements were observed during operation.

Figure 4 shows the comparison between normal elbow movement and patient-assisted movement using the Flexi-Heal system. When compared with normal elbow movement (up to 90° flexion), the patient-assisted movement demonstrated a lower range, as expected due to the device's safety limit of 45°. However, the movement generated by Flexi-Heal remained stable and controlled throughout the session, indicating that the system is safe for repetitive rehabilitation exercises.

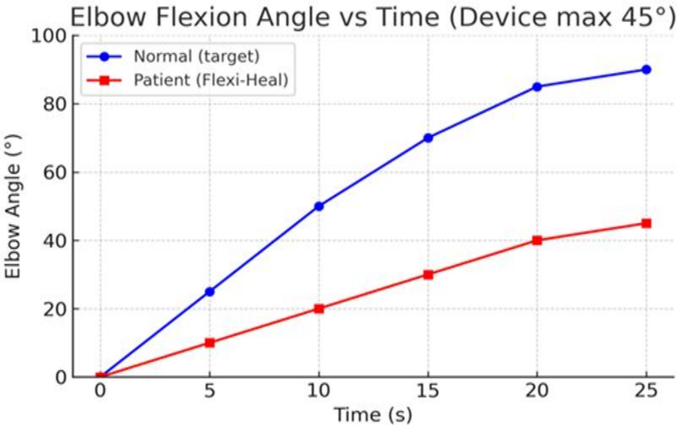

Figure 4: Elbow Flexion Angle Versus Time Comparison Between Normal Movement and Patient-Assisted Movement (Device Maximum 45°).

4.2 IMPROVEMENT IN REHABILITATION PERFORMANCE

The results show a clear improvement in elbow performance over multiple therapy sessions. At the beginning of therapy, the patient could only achieve about 20° of elbow flexion, indicating stiffness and limited muscle control. After several sessions using Flexi-Heal, the maximum flexion angle increased gradually to 45°, as illustrated in Figure 5. This gradual improvement indicates that repeated, assisted movements helped increase joint flexibility and muscle engagement over time.

In terms of repetitions, the patient initially completed only 8 repetitions in the first session. As shown in Figure 6, the number of repetitions increased steadily across subsequent sessions until the patient was able to complete 30 repetitions by the fifth session, matching the reference performance of a normal subject. This finding suggests that Flexi-Heal supports muscle endurance and helps patients perform repeated rehabilitation exercises more confidently.

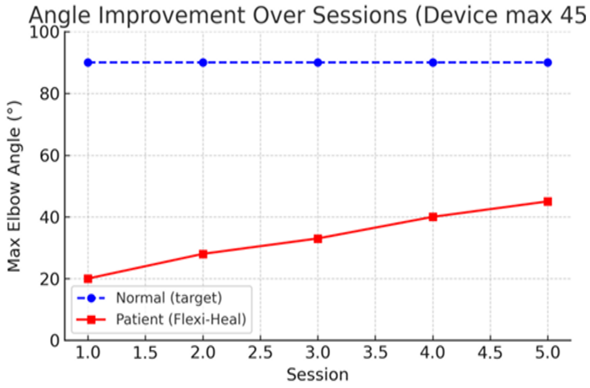

Figure 5: Improvement In Elbow Flexion Angle Over Multiple Rehabilitation Sessions (Device Maximum 45°).

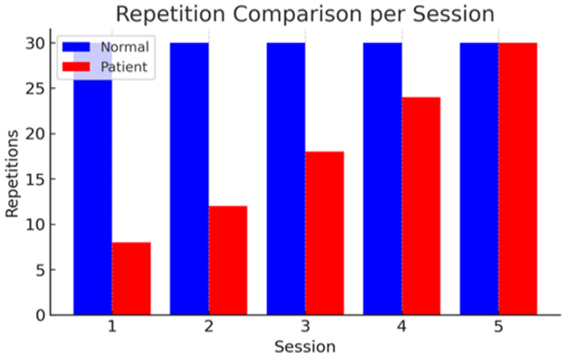

Figure 6: Repetition Comparison Per Therapy Session Between Normal Subject and Patient.

4.3 SYSTEM RELIABILITY

System reliability testing showed that Flexi-Heal achieved a 91% success rate during operation, as presented in Figure 7. The ESP32 microcontroller, servo motor, and power supply operated together effectively without major system failures. Most therapy sessions were completed smoothly without interruption.

The remaining 9% failure rate was mainly caused by brief Wi-Fi disconnections or minor delays in servo response. These issues were temporary and did not stop the therapy session or cause unsafe movement. Overall, the system demonstrated stable performance and is considered reliable for prototype-level home rehabilitation use.

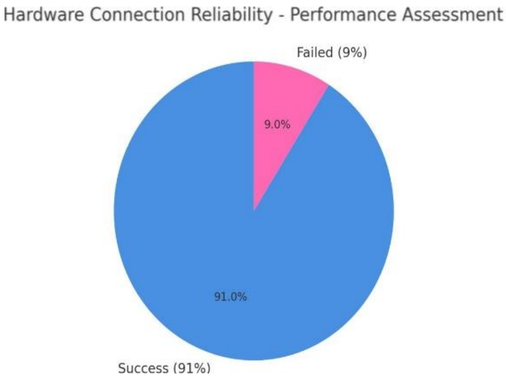

Figure 7: Hardware Connection Reliability and Performance Assessment of the Flexi-Heal System.

4.4 IOT MONITORING AND USER CONTROL

The Blynk mobile application functioned effectively as the control and monitoring interface. Users were able to set elbow angle, repetition count, and start or stop therapy sessions easily through the app. Real-time feedback was successfully transmitted between the ESP32 and the mobile application, allowing progress to be monitored during each session.

The ability to store session data online also supports long-term monitoring and allows therapists or users to review rehabilitation progress. This shows that simple IoT platforms can be effectively used for home-based rehabilitation devices.

5. DISCUSSION

Overall findings from this study indicate that the Flexi-Heal Portable Elbow Rehabilitation System can support early-stage elbow rehabilitation in a safe and controlled manner. The results show gradual improvement in elbow movement and repetition capacity across multiple therapy sessions, suggesting that the device helps patients perform consistent and guided rehabilitation exercises. The system successfully meets its main objective of providing an affordable and portable home-based rehabilitation solution for stroke patients.

The developed prototype consists of an ESP32 microcontroller, a high-torque servo motor, a compact mechanical elbow support structure, an 11.1 V Li-Po battery, a step-down voltage regulator, and the Blynk mobile application. This setup allows users to control therapy parameters such as movement angle and number of repetitions through a smartphone. The mechanical design provides stable elbow support, while the servo motor delivers smooth and repeatable motion suitable for rehabilitation exercises.

Several test scenarios were conducted to evaluate system performance. The patient's elbow flexion angle increased gradually from 20° to 45° over successive sessions, while the number of repetitions improved from 8 to 30 repetitions. These results indicate improved muscle endurance and joint flexibility. System feedback showed a 91% success rate during operation, with stable communication between the ESP32 and the Blynk application. Minor issues such as brief Wi-Fi disconnections and slight servo delays were observed but did not affect the overall therapy process.

Despite the positive results, some weaknesses were identified in the current system. The maximum flexion angle is limited, making the device suitable mainly for early-stage rehabilitation. In addition, system performance depends on Wi-Fi connectivity, and movement speed is fixed. Future improvements should include adjustable angle limits, speed control, improved network stability, and enhanced mechanical comfort to allow wider use and longer therapy sessions.

6. CONCLUSION

This study successfully developed Flexi-Heal, an IoT-enabled portable elbow rehabilitation device, designed to support home-based recovery for stroke patients. The system integrates a high-torque servo motor, ESP32 microcontroller, mechanical elbow support, and IoT connectivity via the Blynk platform, allowing controlled elbow flexion exercises with real-time monitoring through a mobile application. Users can adjust exercise parameters such as elbow angle and repetition count, while session data is recorded to track progress, demonstrating the feasibility of combining mechatronic components with IoT technology for rehabilitation purposes.

Laboratory testing and repeated rehabilitation sessions validated the system's effectiveness, showing stable and controlled elbow movements with gradual improvements in range of motion and repetition performance. The device's real-time monitoring and assisted movement features promote safe and consistent exercise routines. Its portable and cost-effective design enhances accessibility, enabling patients with limited access to clinics to perform rehabilitation at home, while caregivers can remotely track progress.

Despite its strengths, limitations include a fixed movement speed, restricted flexion range, and reliance on Wi-Fi connectivity, which may affect usability in certain environments. Future developments should focus on adjustable speed, extended range of motion, improved mechanical comfort, and enhanced power efficiency. Overall, Flexi-Heal demonstrates strong potential as a scalable, IoT-enabled rehabilitation solution that aligns with Industry 4.0 principles, supporting independent recovery and wider adoption in home-based and tele-rehabilitation programs.

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