International Journal of Reconfigurable and Embedded Systems (IJRES)
Vol. 15, No. 2, July 2026, pp. 553~562
ISSN: 2089-4864, DOI: 10.11591/ijres.v15.i2.pp553-562

Development of internet of things-based exoskeleton for monitoring elbow rehabilitation therapy

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Article Info

Article history:

Received Dec 31, 2024
Revised May 31, 2026
Accepted Jun 21, 2026

Keywords:

Elbow rehabilitation
Internet of things-based exoskeleton
Physiotherapy technology
Real-time monitoring
Servomotor

ABSTRACT

The elbow joint is a complex articulation comprising the humeroulnar and humeroradial joints, facilitating flexion-extension movements essential for daily activities. Leveraging advancements in connected systems and paradigms such as the internet of things (IoT), this study proposes an affordable, effective, and IoT-enabled one-degree-of-freedom (1DOF) elbow exoskeleton for home-based rehabilitation. The exoskeleton is designed to provide a natural range of elbow movements (flexion and extension) while enabling real-time monitoring of rehabilitation progress through mobile applications and web servers. The system collects qualitative data on elbow movements, which are critical in rehabilitation therapy, and enables patients to save their rehabilitation status for future reference. This data can be accessed by doctors remotely, ensuring continuity of care. For patients unable to lift their arm independently, a servomotor provides mechanical assistance, enabling them to achieve desired angles for rehabilitation. The IoT platform generates real-time graphs, offering detailed insights into the recovery process through data analysis. This project is a significant advancement in clinical and healthcare settings, as it reduces dependency on human support or physiotherapists. By integrating IoT technology, the proposed exoskeleton ensures effective, autonomous, and data-driven rehabilitation for elbow joint recovery.

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1. INTRODUCTION

The elbow joint is a complex structure composed of bones, cartilage, ligaments, and synovial fluid, which collectively facilitate a wide range of movements essential for daily activities. Elbow injuries are prevalent, with many individuals experiencing minor injuries throughout their lives, often manifesting as symptoms such as pain, swelling, and restricted movement [1], [2]. The causes of these injuries are multifaceted, encompassing sports-related activities, occupational hazards, and accidents at home, with tendonitis and conditions like tennis elbow being particularly common [3], [4]. The epidemiology of elbow injuries highlights that trauma is a significant contributor, leading to complications such as stiffness and contracture, which complicate recovery [3], [5], [6].

Recovery from elbow injuries is contingent upon various factors, including the type and severity of the injury, the patient's overall health, and the rehabilitation methods employed. Effective rehabilitation typically focuses on restoring the range of motion, particularly flexion and extension, which are critical for functional recovery [1], [2]. The triceps brachii primarily facilitates extension, while flexion is achieved through the coordinated action of the biceps brachii, brachialis, and brachioradialis [1], [2]. Rehabilitation strategies often involve physical therapy and targeted exercises to enhance strength and mobility, but the process can be prolonged and requires consistent monitoring [1], [7]. Personalized rehabilitation using adaptive generative models has demonstrated promising improvements in individualized robotic assistance [8].

Recent advancements in rehabilitation technology, particularly the development of exoskeletons, have introduced innovative approaches to elbow rehabilitation. Lightweight cable-driven actuation has recently emerged as an effective solution for reducing device weight while maintaining rehabilitation performance [9]. Recent developments also demonstrate that artificial intelligence significantly improves wearable upper-limb exoskeletons through adaptive control, intention recognition, and personalized rehabilitation strategies [10]. Advanced motion-generation algorithms have recently been proposed to improve trajectory planning and provide smoother coordinated movements for upper-limb rehabilitation exoskeletons [11]. These devices, originally designed for industrial and military applications, are now being adapted for medical use, providing mechanical assistance to patients recovering from elbow injuries [12], [13]. Proper human–exoskeleton alignment and coupling dynamics are also essential for safe rehabilitation and effective torque transmission [14]. The specific exoskeleton system discussed employs a one-degree-of-freedom (1DOF) mechanism to assist with elbow flexion and extension. Recent modular exoskeleton designs have further improved adaptability to different patients while reducing mechanical constraints [15]. Advanced adaptive admittance control has recently been shown to improve rehabilitation performance by adjusting robot assistance according to patient intention [16]. This design not only supports the physical rehabilitation process but also collects data through internet of things (IoT) platforms, enabling remote monitoring of recovery [12], [17]. Recent studies have shown that machine-learning approaches can significantly improve movement-intention detection for intelligent rehabilitation robots [18]. The integration of IoT technology into these systems further enhances their utility by enabling real-time monitoring of patient progress, allowing healthcare providers to tailor rehabilitation protocols based on continuously updated data [7], [19]. Such innovations represent a shift towards more personalized and data-driven rehabilitation strategies, which can significantly improve outcomes for patients recovering from elbow injuries [7], [19]. By leveraging these technologies, healthcare providers can enhance the efficiency of rehabilitation while empowering patients to take an active role in their recovery process. Emerging self-powered wearable sensing technologies are expected to further improve long-term rehabilitation monitoring without increasing system complexity [20].

This paper introduces an IoT-based exoskeleton system specifically designed for elbow rehabilitation. The device uses a 1DOF mechanism to assist flexion and extension movements of the elbow. Real-time data collected through IoT platforms such as Blynk and ThingSpeak allows patients and clinicians to monitor the recovery process from any location. This innovation aims to reduce the burden on healthcare providers while empowering patients to take greater control over their rehabilitation.

2. RESEARCH METHOD

2.1. Hardware design and instruments

The IoT-based elbow exoskeleton system was designed to prioritize portability and user comfort. Lightweight materials were used for the frame, which was constructed using a durable DIN rail as the base structure shown in Figure 1. The frame was secured with hexagonal screws and equipped with four adjustable straps to ensure a snug and secure fit on the forearm. A servomotor with metal gearing, capable of lifting up to 5 kg, was incorporated to provide mechanical assistance for elbow movements.

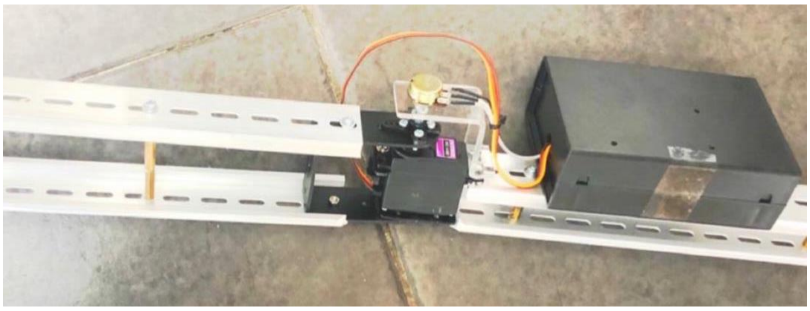


Figure 1. Elbow exoskeleton base structure

At the core of the system is the NodeMCU ESP8266 microcontroller, responsible for processing and transmitting information between input and output components. The NodeMCU is an open-source Lua-based firmware and development board tailored for IoT applications. It features the ESP-12E module, which houses the ESP8266 chip with a Tensilica Xtensa 32-bit LX106 RISC microprocessor. This microprocessor operates at an adjustable clock frequency of 80 MHz to 160 MHz, supports real-time operating system (RTOS), and includes 128 KB of random access memory (RAM) and 4 MB of flash memory for data and program storage. The NodeMCU's high processing power, integrated Wi-Fi, and deep sleep functionality makes it an ideal choice for IoT projects. The board can be powered via a micro-USB jack or an external supply pin (VIN), enhancing its versatility in different operational environments.

A potentiometer was integrated into the system to measure angular movements of the elbow joint though recent rehabilitation systems have integrated dedicated angle sensors to improve motion tracking accuracy and autonomous training performance [21]. The potentiometer outputs changes in analog-to-digital converter (ADC) values within a range of 0–1023 (10-bit resolution). Using the Arduino integrated development environment (IDE) map() function, these ADC values are converted into corresponding angle values. Specifically, a minimum ADC value of 420 is mapped to 0°, and a maximum value of 920 is mapped to 130°. This mapping allows the system to display real-time angular positions on IoT platforms, enabling precise monitoring of rehabilitation progress.

To provide mechanical assistance, a servomotor was employed due to its ability to precisely control angular position, velocity, and acceleration. The servomotor consists of an electric motor, a position feedback sensor, and a controller, enabling accurate closed-loop control. This component plays a vital role in elbow rehabilitation by assisting flexion and extension movements and providing the required torque for patients who are unable to perform these movements independently. To further improve rehabilitation performance, sensor information integrated with cloud-based telerehabilitation has recently been introduced, enhancing the accuracy of remote patient assessment and enabling continuous monitoring by clinicians with similar cloud-assisted rehabilitation platforms have demonstrated the growing importance of telemonitoring for home-based therapy [22]. Objective kinematic assessment using robotic exoskeletons enables quantitative evaluation of rehabilitation progress and supports evidence-based clinical decision making [23].

2.2. Arduino integrated development environment

The Arduino IDE serves as the primary software for programming and interfacing with the hardware components. The IDE includes a text editor for writing code, a toolbar for common functions, and a console for displaying messages and errors. Programs, referred to as "sketches," are written in the text editor and saved with the .ino file extension. The IDE allows users to compile, verify, and upload code to the NodeMCU ESP8266 microcontroller. Additionally, it facilitates communication with the hardware through the serial monitor, making it a vital tool for system programming and debugging.

2.3. Bylnk (free cloud internet of things platform)

Blynk is a platform with iOS and Android applications designed to control and monitor hardware projects remotely. It provides a digital dashboard where users can create custom interfaces by dragging and dropping widgets such as sliders, buttons, and graphs. After downloading the Blynk app, a project dashboard can be created, and the required widgets configured. In this project, a slider widget is used to adjust the servomotor's angle, while a gauge widget displays the corresponding angle value. By integrating Blynk with the Arduino IDE, real-time control and monitoring of the exoskeleton system are achieved.

2.4. ThingSpeak (internet of things platform)

ThingSpeak is an IoT analytics platform used for aggregating, visualizing, and analyzing live data streams in the cloud. It enables real-time data visualization through interactive graphs and offers integration with MATLAB for advanced analytics. ThingSpeak is employed in this project to display angular data generated by the potentiometer. Using the hypertext transfer protocol (HTTP) and message queuing telemetry transport (MQTT) protocols, data is stored and retrieved from the cloud, allowing users to monitor rehabilitation progress through live graphs accessible via a web interface.

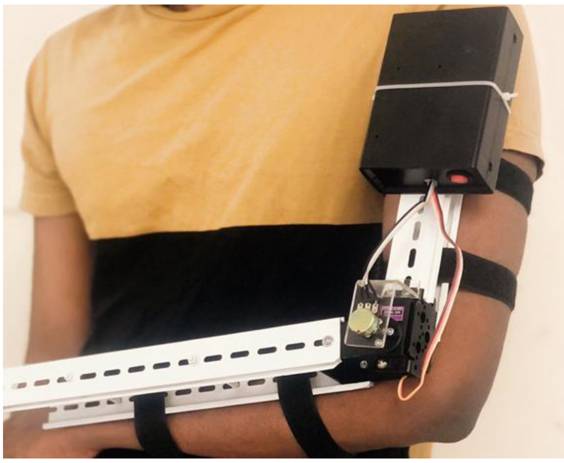
2.5. Method of process

The system implementation begins with hardware assembly. The components, including the potentiometer, servomotor, and NodeMCU ESP8266, are secured and integrated into the exoskeleton structure. The Arduino IDE is used to write and verify the program, which is subsequently uploaded to the NodeMCU microcontroller.

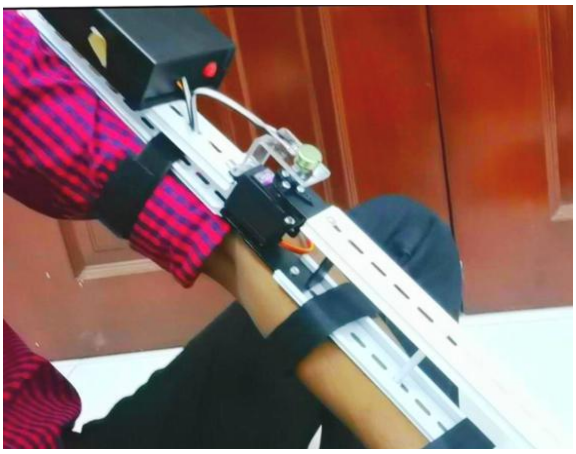
The exoskeleton is then worn on the injured arm. Initially, the servomotor switch remains off, allowing patients to move their elbows manually for flexion and extension exercises depicted in Figure 2. During this process, the potentiometer detects angular changes, converting the ADC values to angle values using the map() function in the Arduino IDE. These values are displayed in real-time on ThingSpeak and ThingView.

When the servomotor switch is activated, the motor assists patients who are unable to perform rehabilitation movements independently. It facilitates elbow flexion and extension within a range of 0° to 130°. Patients can set their desired rehabilitation angle using the Blynk slider widget, while the gauge displays the corresponding angle in real time. This IoT-enabled system continuously monitors and stores rehabilitation data in the cloud, allowing patients and healthcare professionals to track rehabilitation progress remotely. The recorded data can also be exported as comma-separated values (CSV) files for further analysis and reporting. In addition, recent rehabilitation interfaces have emphasized ergonomic design to enhance patient comfort and support long-term usability [24].

Figure 2(a) illustrates the elbow flexion movement, where the forearm moves upward toward the upper arm, whereas Figure 2(b) depicts the extension movement, in which the forearm returns to its initial straight position. Both movements constitute the fundamental rehabilitation exercises facilitated by the proposed exoskeleton system.



(a)



(b)

Figure 2. Elbow exoskeleton movements; (a) flexion and (b) extension

2.6. Project flowchart

The flowchart in Figure 3 provides a diagrammatic representation of the project's workflow, illustrating the step-by-step processes involved. It visually represents key stages, including hardware setup, programming, data processing, and rehabilitation monitoring, helping streamline the design and implementation phases.

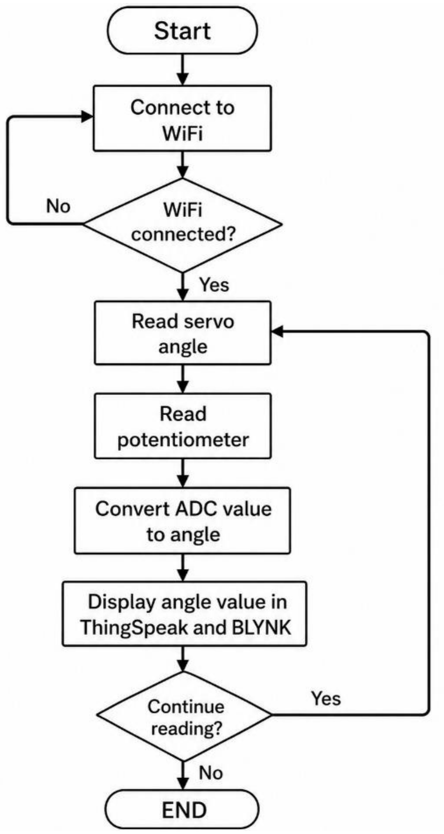


Figure 3. Project flowchart

3. RESULTS AND DISCUSSION

3.1. Progress tools

The Proteus design suite was employed to simulate the hardware design, integrating libraries specific to NodeMCU ESP8266. The system schematic included essential components such as a regulator, potentiometer, and servomotor. For programming, the Arduino IDE facilitated the integration of IoT platforms, with Blynk and ThingSpeak offering user-friendly interfaces. ThingView can be used to provide convenient mobile-based extension of the ThingSpeak data visualization, ensuring accessibility for users.

3.2. Application setup

The Blynk application allowed patients to download the app, configure widgets such as sliders and gauges, and integrate it with the exoskeleton system using an authentication token. This platform enabled users to control the servomotor's angle and monitor real-time data, enhancing interactivity in the rehabilitation process. Complementing this, ThingSpeak generated real-time graphs of elbow movements, with data securely stored in the cloud for further analysis and exportable as CSV files for detailed evaluation using software like Excel. Additionally, ThingView utilized the channel ID and API key from ThingSpeak to seamlessly replicate real-time data on mobile devices, providing convenient access to rehabilitation progress for both patients and clinicians.

3.3. Data analysis

Real-time graphs displayed flexion (0° to 140°) and extension (140° to 0°) angles, highlighting the system's ability to track elbow joint movements. The data was exportable to CSV format for further processing, enabling healthcare providers to monitor progress and identify recovery trends. Patients could visualize their rehabilitation journey through ThingSpeak or ThingView, fostering engagement in their recovery process.

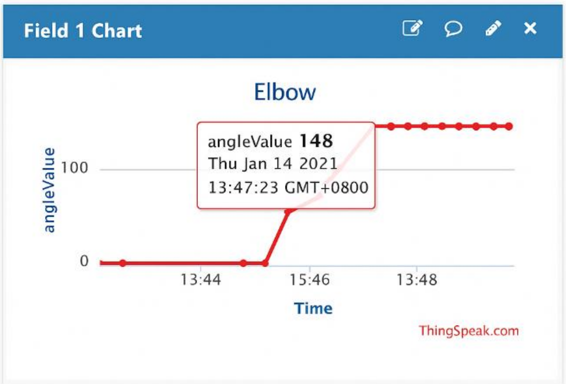
3.4. Project analysis

The real-time graph provides evidence of the successful implementation of the proposed system and demonstrates that the project objectives have been achieved. The recorded data focus on a single degree of freedom (DOF), representing the elbow's flexion and extension movements. In normal elbow anatomy, extension typically ranges from 0° to 10°, while flexion ranges from approximately 130° to 140°. Throughout the rehabilitation process, the elbow joint angle serves as a key parameter for monitoring joint position and evaluating patient recovery. Consistent and controlled flexion–extension movements within the expected anatomical range indicate improvements in motor function and rehabilitation progress. Furthermore, adaptive assist-as-needed control strategies have been shown to improve trajectory tracking accuracy while minimizing unnecessary robotic assistance, thereby promoting more active patient participation during therapy [25].

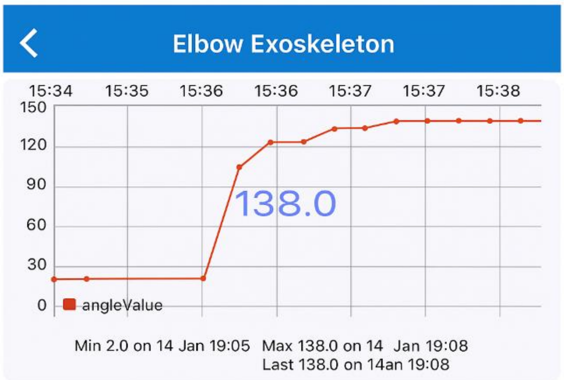
3.4.1. Flexion (ThingSpeak and ThingView)

Flexion at the elbow joint refers to the movement from a fully extended position toward an upper angular position. The data analyzed through the IoT platform correspond to angular ranges of 0°, 0–90°, 90–140°, and 0–140°. These values are categorized as flexion since they represent the ascending motion of the forearm from the lowest angle (0°) to the highest (140°).

Embedded intelligent control enables rehabilitation devices to respond dynamically to user intention and improves interaction quality [26]. Figure 4 illustrates the flexion data as visualized on the IoT monitoring platforms. Specifically, Figure 4(a) presents the real-time flexion data displayed on the ThingSpeak platform, showing the variation in elbow angle during movement, whereas Figure 4(b) provides the corresponding visualization on the ThingView mobile application, offering convenient access and monitoring for both patients and clinicians.



(a)



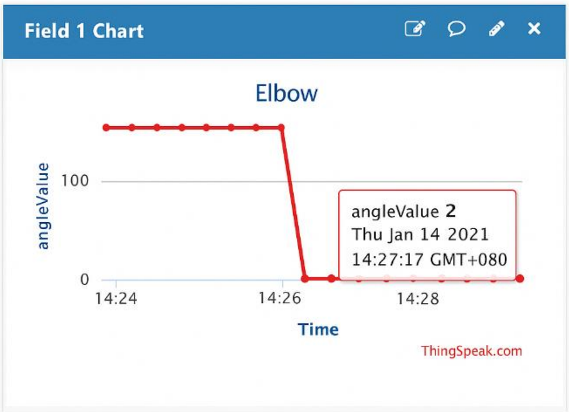
(b)

Figure 4. Flexion at 0-140°; (a) ThingSpeak and (b) ThingView

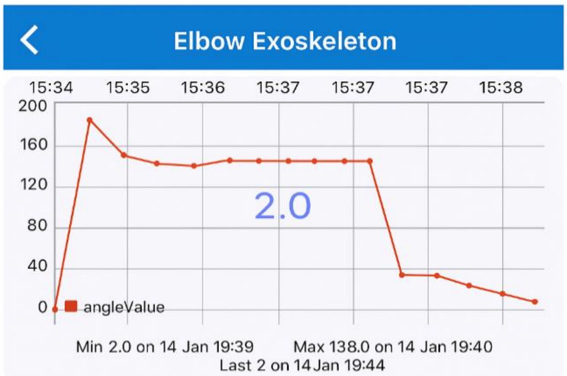
3.4.2. Extension (Thingspeak and ThingView)

Extension at the elbow joint refers to the movement that increases the joint angle, returning the forearm from a flexed position to the anatomical, straight alignment. The analyzed data include angular ranges of 140°, 140–90°, 90–0°, and 140–0°, which are categorized as extension since they represent the descending motion from the highest angle (140°) to the lowest (0°).

This data was analyzed using IoT platforms such as ThingSpeak and visualized through Excel and the ThingView mobile application. Figure 5 illustrates the extension data displayed across these platforms. Specifically, Figure 5(a) shows the real-time extension data of the elbow joint as captured on the ThingSpeak platform, while Figure 5(b) presents the same data visualized on the ThingView mobile application. These figures demonstrate the system's capability to monitor the extension phase of rehabilitation exercises in real time.



(a)



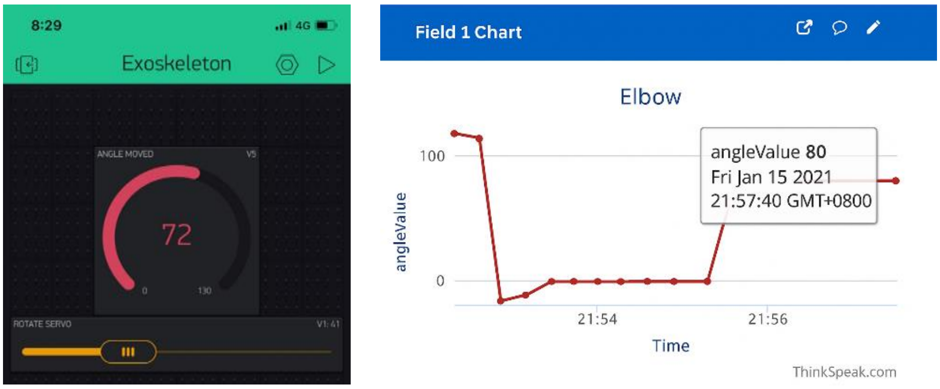
(b)

Figure 5. Flexion at 0-140°; (a) ThingSpeak and (b) ThingView

3.4.3. Rotate servo using Blynk

For patients unable to move their elbow independently, such as stroke patients with nerve damage, the IoT-based elbow exoskeleton provides crucial assistance. These patients typically rely on physiotherapists for flexion and extension exercises. The Blynk application offers a solution by allowing users to control the servomotor using a slider. The slider range is from 0 to 130°, and patients can set their desired angle (e.g., 90°) by moving the slider. The angle is displayed on a gauge labeled "Angle Moved" within the Blynk app.

Once the movement is initiated, the corresponding data are simultaneously transmitted and monitored on the ThingSpeak platform. The system supports continuous data acquisition and allows exporting the collected information in CSV format for further analysis in Excel. Patients and clinicians can plot continuous graphs to evaluate recovery trends and rehabilitation progress in detail. Figure 6 illustrates the system's functionality and its capability to assist and monitor elbow rehabilitation effectively. Specifically, Figure 6(a) shows the servomotor control interface in the Blynk mobile application, where the user adjusts the desired elbow angle using a slider, while Figure 6(b) displays the corresponding real-time data visualization on the ThingSpeak platform, confirming synchronized control and monitoring during the rehabilitation process.



(a) (b)

Figure 6. Data visualization; (a) Blynk and (b) ThingSpeak

4. CONCLUSION

The IoT-based elbow exoskeleton developed in this project marks a significant advancement in rehabilitation technology, enabling real-time monitoring and assistance for patients recovering from elbow injuries. Utilizing a NodeMCU ESP8266 microcontroller, the device provides remote access to rehabilitation data for healthcare providers, enhancing both patient engagement and the effectiveness of rehabilitation exercises. Positive user feedback underscores the exoskeleton’s comfort and usability, although limitations such as a small sample size and short intervention duration were noted. Future research could expand the study population, evaluate long-term impacts, and improve the device's range of motion. This project has demonstrated the transformative potential of IoT integration in rehabilitation, paving the way for further innovations to meet patient and provider needs.

ACKNOWLEDGMENTS

The authors would like to thank Universiti Teknikal Malaysia Melaka (UTeM) for the support given to this research.

FUNDING INFORMATION

Authors state no funding involved.

AUTHOR CONTRIBUTIONS STATEMENT

This journal uses the Contributor Roles Taxonomy (CRediT) to recognize individual author contributions, reduce authorship disputes, and facilitate collaboration.

Name of Author	C	M	So	Va	Fo	I	R	D	O	E	Vi	Su	P	Fu
Geevanthran A/L Vegurgama	✓	✓	✓	✓	✓	✓		✓	✓	✓			✓	
Mohd Razali Mohamad Sapiee		✓				✓		✓	✓	✓	✓	✓		
Khalil Azha Mohd Annuar	✓		✓	✓			✓			✓	✓		✓	✓

C : **C**onceptualization
M : **M**ethodology
So : **So**ftware
Va : **Va**lidation
Fo : **Fo**rmal analysis
I : **I**nvestigation
R : **R**esources
D : **D**ata Curation
O : Writing - **O**riginal Draft
E : Writing - Review & **E**diting
Vi : **Vi**sualization
Su : **Su**pervision
P : **P**roject administration
Fu : **Fu**nding acquisition

CONFLICT OF INTEREST STATEMENT

Authors state no conflict of interest.

DATA AVAILABILITY

Data availability is not applicable to this paper as no new data were created or analyzed in this study.

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