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Design and Implementation of a Wearable System for Home-Based Rehabilitation

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***Abstract*—This paper presents the design and implementation of a modular, low-cost, home-based rehabilitation device intended for patients undergoing hip or knee replacement therapy. The system enables remote monitoring and feedback between patients and physiotherapists by capturing biomechanical data through a wearable orthosis equipped with Inertial Measurement Units (IMUs) and flex sensor. All the data acquired through these sensors is collected using an ESP32 micro-controller and, together with the use of libraries like socket, the information will be stored in order to analyze and monitor the patient's progress. Results showed 90-100% accuracy in detecting hip/gait movements but revealed limitations in dynamic knee flexion, highlighting areas for sensor optimization. The goal is to provide active feedback on their rehabilitation or to correct any issues in case the exercises are not being performed properly.**

***Index Terms*—Biomedical engineering, flex sensor, hip replacement, home-based rehabilitation, inertial measurement units (IMUs), knee replacement, microcontroller, physiotherapy, post-operative rehabilitation, socket.**

I. Introduction

In recent years, the global burden of musculoskeletal disorders has continued to increase, posing significant challenges to public health systems and driving a growing demand for long-term rehabilitation services. Total knee and hip replacements are among the most commonly performed orthopedic procedures worldwide, particularly in aging populations affected by advanced osteoarthritis, trauma, or degenerative joint diseases [1]. Postoperative recovery from these surgeries requires strict adherence to individualized rehabilitation programs, where the accurate execution of therapeutic exercises is crucial for restoring mobility, alleviating pain, and regaining functional independence [2].

According to World Health Organization (WHO), rehabilitation is defined as a set of interventions designed to optimize functioning and reduce disability in individuals with health conditions in interaction with their environment [3]. It is a core component of universal health coverage, alongside health promotion, disease prevention, treatment, and palliative care. Rehabilitation is essential for people of all ages recovering from injury, illness, or surgery, and should not be considered a luxury or a last-resort intervention [3].

Despite its importance, access to rehabilitation remains limited in many regions. WHO estimates that 2.4 billion people globally could benefit from rehabilitation, yet in numerous low and middle-income countries, including Costa Rica, more than half of those in need do not receive appropriate services. Barriers include insufficient funding, a lack of national policies, long waiting times, urban concentration of services, high out-of-pocket costs, and shortages of qualified professionals and assistive technologies [3].

In Costa Rica, patients often experience prolonged waiting times within the public healthcare system, delaying recovery and reducing the effectiveness of treatment [2]. This situation highlights the urgent need for accessible technological solutions that can complement conventional rehabilitation methods and support patients in home-based rehabilitation.

This paper presents the design and implementation of a portable, low-cost rehabilitation system for patients recovering from hip and knee replacements. The device integrates wearable sensors to track biomechanical activity and transmit data remotely, enabling real-time feedback and clinical monitoring without requiring continuous in-person supervision.

This paper outlines the development of the proposed system, including its conceptual design, sensor selection and integration, and the initial testing phase. The goal is to present a scalable, reliable, and user-centered tool suitable for deployment in non-clinical settings.

II. Methods

This project aims to develop an at home rehabilitation device that enables remote monitoring and feedback between patients receiving hip or knee replacement therapy and their respective physiotherapists. The system collects biomechanical data through wearable sensors strategically placed on key body regions, which are transmitted to a centralized database for subsequent analysis, thereby forming a virtual rehabilitation environment [4].

A. Exercise Selection and Measurement Strategy

To evaluate rehabilitation progress, a set of clinically recommended exercises was selected for patients with replacements based on official protocols of the Costa Rican National Rehabilitation Center (CENARE) [5],[6], [7]. These exercises target different stages of recovery and focus on muscle strengthening, joint mobility, and flexibility.

Based on their clinical relevance and suitability for sensor-based tracking, the following exercises were selected. These involve the use of inertial measurement units (IMUs) and a flex sensor to monitor motion parameters essential to rehabilitation:

- Straight-leg raise: The patient raises the extended leg while lying down. This exercise is monitored using IMUs on the thigh and hip to capture elevation angle and angular velocity.
- Hip Abduction/Adduction: The patient moves the leg away from and toward the midline while lying on their back. IMUs on the thigh record lateral angular displacement and movement range.
- Knee Extension (Seated): With the patient seated, the leg is extended forward. An IMU on the lower leg and a flex sensor behind the knee capture the knee extension angle and movement smoothness.
- Knee Flexion (Standing): The patient flexes the knee while standing. IMUs on the thigh and lower leg track angular change, and the flex sensor measures peak knee bending.
- Walking (Gait): The patient performs a walking task over a flat surface. IMUs placed on the hips and lower limbs measure joint angles, stride symmetry, and cadence.

To ensure consistent placement and minimize user error, all sensors are embedded into a wearable garment resembling a compression panty. This setup allows for reproducible sensor positioning across sessions and enhances user comfort.

The device was employed during the execution of the selected exercises for evaluation purposes. For each exercise, ten correctly performed repetitions and five incorrectly executed ones were recorded, in order to identify key variables that differentiate proper from improper execution. This information is essential for providing feedback to the patient and enabling real-time correction during the rehabilitation process.

B. Data Collection and Communication

The data collection and communication architecture of the system has been structured to facilitate real-time remote monitoring of the rehabilitation processes through a low-power modular infrastructure.

A variety of sensors, including IMUs and a flex sensor, are connected to the ESP32 and sampled at frequencies ranging from 50-100 Hz, in line with the current biomechanical monitoring practices for walking and rehabilitation tasks [8]. These sensors provide comprehensive biomechanical data, detailing kinematic variables, muscle activation patterns, joint flexion, and mechanical strain.

Sensor signals are received by an ESP32 microcontroller, a Wi-Fi enabled system-on-chip widely adopted in wearable system technologies due to its optimal balance between computational efficiency and wireless connectivity [9]. The ESP32 is programmed using the Arduino IDE, offering a flexible and accessible plataform for the rapid prototyping and integration of the biomedical sensors network.

The microcontroller performs basic signal preprocessing, including timestamping, signal averaging, and data packet structuring. The processed data is encapsulated in CSV format an transmitted over Wi-Fi using socket communication protocols. This setup enables real-time streaming of sensor information from the ESP32 to a host computer functioning as a local server.

During the testing phase, sockets are employed as the primary method for client-server communication. In this configuration, the ESP32 acts a client device that establishes a connection with the server, exchanges data, and then terminates the connection. This client-server interaction allows the host machine to receive and log the transmitted sensor data continously for further analysis and visualization. Socket-based communication was chosen for its simplicity and low-latency characteristics during initial testing, with future extensions planned for API and database integration.

The design is inherently modular and scalable, allowing seamless integration of additional sensor modalities or communication endpoints as the system evolves [10].

C. Replicability and Scalability

All hardware components used in the design, such as the ESP32 and sensors, are commercially available and affordable, ensuring the system can be replicated with different configurations [11]. The use of open-source software such as the Arduino IDE, socket, Python, and , enhances accessibility and flexibility in deployment.

III. Results and discussion

The first implementation of the proposed rehabilitation device design as part of the initial testing phase is shown in Fig 1. This figure illustrates the placement of the IMUs and flex sensors, and the other components of the system, showing the overall design of the prototype. As mentioned before, this configuration was chosen to ensure comfort, repeatable sensor positioning, and ease of use for the patient during rehabilitation sessions.

It is worth mentioning that the entire wiring system will be organized and arranged with the same objective of ensuring patient comfort, as well as protecting the system.

In line with the project objectives, the results demonstrate the feasibility and accessibility of home-based rehabilitation for patients recovering from knee and hip replacement surgeries. The system's performance in detecting and evaluating movements was assessed across various rehabilitation exercises commonly prescribed in post-surgical recovery protocols.

TABLE I
DETECTION AND CLASSIFICATION PERFORMANCE FOR EACH REHABILITATION EXERCISE, INCLUDING DETECTION ACCURACY, QUALITY ASSESSMENT, AND CONFUSION MATRIX VALUES

Exercise	Detection	Quality	True Positives	True Negatives	False Positives	False Negatives
Straight-leg raise	70%	80%	7	5	0	3
Hip Abduction/Adduction	90%	87%	9	4	1	1
Knee Extension (Seated)	60%	73%	6	5	0	4
Knee Flexion (Standing)	40%	53%	4	4	1	6
Walking (Gait)	100%	87%	10	3	2	0

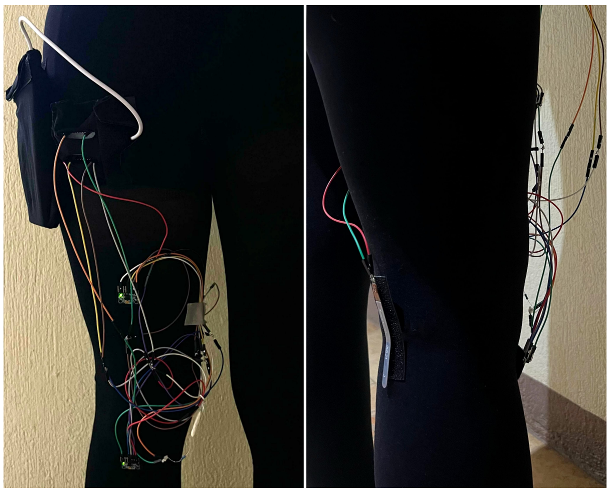

Fig. 1. Final prototype of the wearable rehabilitation system for the initial testing phase.

The results of the system, summarized in Table I, demonstrate varying performance across the six rehabilitation exercises, including true positives, true negatives, false positives, and false negatives. Among these, hip abduction/adduction and walking (gait) showed the highest levels of detection and quality accuracy. Specifically, hip abduction/adduction achieved a detection accuracy of 90% (9 true positives, 1 false positive, 1 false negative), while the walking exercise achieved perfect detection accuracy (100%, 10 true positives, 2 false positives, 0 false negatives).

In contrast, the knee flexion (standing) exercise showed the lowest performance, with a detection accuracy of only 40%, suggesting that the algorithm may struggle with more dynamic standing movements. On the other hand, the knee extension (seated) exercise resulted in a higher detection accuracy compared to standing flexion, although the quality remained moderate. This may be due to the limited range of motion in seated positions, which can affect the clarity of the signal and the algorithm's ability to classify the exercise accurately.

In addition, some graphs of the collected data are presented, with particular emphasis on the exercises yielding the highest and lowest detection performances, walking and knee flexion, respectively. Although these two cases are highlighted, a consistent analysis methodology was applied across all exercises. The goal is to identify potential sources of measurement error and propose improvements to the system. In this context, issues were noted with the flex sensor, suggesting that either the data it provides may lack accuracy or that it may not be the most suitable sensor for evaluating this specific movement parameter.

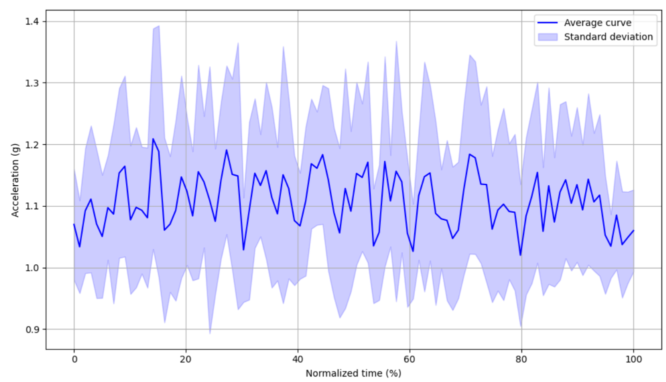

Fig. 2. Normalized acceleration profile for the gait exercise across 10 repetitions.

The interpolated and normalized acceleration data from ten walking trials demonstrated a high level of consistency. The overall mean value across all time points was 1.11, with an average standard deviation of 0.13, indicating low variability between repetitions. The maximum average value recorded was 1.21, while the minimum was 1.02. These results support the system's robust performance in detecting the gait exercise, as low variability and consistent temporal pattern across repetitions facilitated reliable classification.

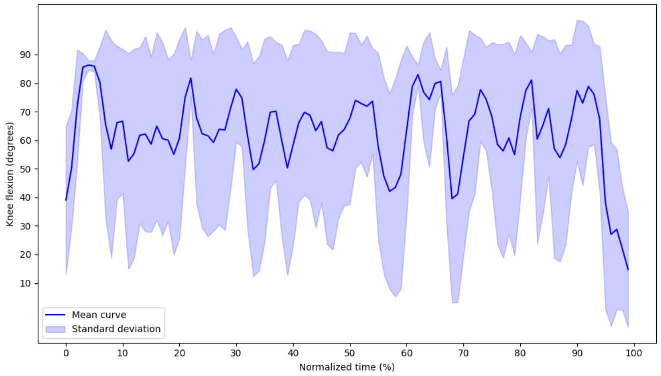

Fig. 3. Interpolated knee flexion angle versus time for 10 repeated exercises.

The interpolation of ten data points from repeated knee flexion exercises resulted in a pointwise mean flexion angle ranging from 14.73° to 86.33°, with an overall mean of 62.92° and a standard deviation of 27.51°. The standard deviations at each point indicates considerable variability in movement e across repetitions.

This variability likely contributed to the relatively low detection accuracy of approximately 40%, as inconsistent kinematic patterns reduce the model's ability to reliably recognize the flexion movement. Furthermore, the broad range between the maximum and minimum mean flexion values suggests that some repetitions failed to achieve a comparable range of motion, potentially confounding the classification algorithm. Using only 10 interpolated points may also limit the capture of the movement's full dynamics, reducing the resolution needed for precise classification.

IV. Recommendations

- In future work, it is recommended to incorporate additional sensors, such as electromyography (EMG), to enable the acquisition of more comprehensive data. This would allow better monitoring and analysis of the rehabilitation exercises performed by the patient.
- It is recommended to expand the set of included exercises in order to cover a broader spectrum of the rehabilitation process. This would enable the device to offer greater functional coverage and monitor a wider range of movements and motor patterns, thereby increasing its clinical utility and adaptability to diverse therapeutic needs.
- It is recommended to replace the socket-based communication system with a dedicated Application Programming Interface (API) and a remote database such as MongoDB. This modification would support the simultaneous management of data from multiple patients, eliminate the dependency on a local host computer, and facilitate cloud-based storage for long-term data analysis. Additionally, the development of a mobile application and a web platform, would enable real-time visualization of patient feedback, improving accessibility and enhancing the overall user experience for both clinicians and patients.
- In future developments, it is proposed that the device be capable of simultaneously collecting data from both lower limbs to enable real-time bilateral comparison. This functionality would facilitate the identification of asymmetries or compensatory pattern, such as the overuse of one leg, which are critical for achieving balance and effective rehabilitation. Such an enhancement would contribute to more comprehensive patient monitoring and improved therapeutic outcomes.

V. Conclusion

This work details the first steps of development and implementation of a modular, wearable, home-based rehabilitation device designed for patients undergoing hip or knee replacement. The system allows remote tracking of biomechanical data during clinically recommended exercises through IMUs and a flex sensor.

Test showed the device can accurately detect and evaluate each rehab exercise. For example, Hip Abduction/Adduction achieved high quality and detection rates of over 85%, demonstrating the system's reliability for remote monitoring. However, movements like knee flexion, had a lower accuracy, indicating the need to improve the device and algorithms.

The use of a socket-based communication setup with an ESP32 microcontroller worked well during trials. Still, the current system depends on a local server and lacks important characteristics like persistent data storing and scalability .

Beyond technical performance, this system addresses a critical gap in global rehabilitation access by enabling home-based rehabilitation with remote supervision. Its implementation has the potential to reduce healthcare care costs, minimize patient travel burdens, and alleviate pressure on overburdened clinical facilities.

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