KNEEIoT

Automated knee movement monitoring using IoT for Telerehabilitation

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Abstract—**Knee injury rehabilitation typically requires frequent, inconvenient hospital visits for supervised physiotherapy. To address this, this work introduces an Internet of Things (IoT) based knee tele-rehabilitation system for remote patient monitoring and therapy. Powered by an ESP32 microcontroller, the system integrates motion and physiological sensors to track joint movement, heart rate, oxygen saturation, and body temperature in real time. A built-in stepper motor mechanism provides physical movement assistance, guided by visual and auditory alerts. Connected to a cloud-based Android application, the system operates in both manual and automatic modes. Notably, it automatically activates assisted movement upon detecting repeated incorrect exercise attempts, and features a safety override that pauses operation during abnormal physiological readings. By merging real-time sensing, automation, and remote communication, this system enhances the accessibility, safety, and efficiency of knee rehabilitation.**

Index Terms— **Internet of Things, tele rehabilitation, knee therapy, remote monitoring, physiotherapy automation.**

I. Introduction

Knee injury and post-surgical recovery rely heavily on structured physiotherapy to restore mobility and strength. Traditionally, this requires regular clinic visits for therapist guidance and monitoring. However, long-term or remote patients often find this conventional approach inconvenient and difficult to maintain.

To bridge this gap, Internet of Things (IoT) technology enables remote healthcare by connecting sensors, embedded devices, and cloud platforms. This allows healthcare professionals to monitor patient activity and progress in real time outside the clinic.

This study proposes an integrated IoT platform combining motion monitoring, physiological sensing, and motor-assisted therapy. Patients perform prescribed exercises at home while their movement and health data are transmitted to a cloud server. Equipped with built-in safety mechanisms to keep sessions within secure limits, this system makes knee rehabilitation more accessible without sacrificing effective guidance and supervision.

II. Related Works

The development of tele-rehabilitation systems has gained significant traction in recent years, driven by rapid advancements in Internet of Things (IoT) technologies and wearable healthcare devices. To support remote physiotherapy and continuous patient monitoring, researchers have explored various approaches ranging from sensor-based tracking to robotic assistance.

1. IoT Frameworks and Wearable Technologies in Healthcare

The foundation of remote patient monitoring relies heavily on cloud connectivity and sensor networks.

- **Architectural Foundations:** Gubbi et al. [2] detailed the overarching architecture and vision of the Internet of Things (IoT), demonstrating how merging connected devices, cloud computing, and robust network protocols can create intelligent, real-time data analysis systems across multiple domains, including healthcare.
- **Remote Monitoring Frameworks:** Expanding on this ecosystem, Islam et al. [3] proposed a dedicated IoT framework for remote patient care. Their work demonstrated that continuous observation of physiological parameters via cloud platforms enables early detection of anomalies, significantly enhancing the quality of decentralized patient care.
- **Sensor-Driven Assessment:** Focus shifted toward practical clinical application in the work of Patel et al. [1], who provided a comprehensive review of wearable sensor technologies. They emphasized that collecting physiological and kinematic (motion-related) data allows clinicians to objectively evaluate patient recovery and maintain continuous observation outside traditional clinical environments.

2. Robotic Rehabilitation and Telemedicine

Beyond passive monitoring, active therapeutic intervention has been addressed through robotics and communication technologies.

- **Motor-Assisted Rehabilitation:** Kiguchi and Hayashi [4] developed an exoskeleton-based system engineered to assist human joint movement. By utilizing robotic mechanisms to guide patients through controlled therapeutic exercises, such systems remarkably improve movement precision and reduce a patient's dependency on the physical presence of a therapist. However, the high cost, bulkiness, and structural complexity of these robotic systems often restrict their deployment to specialized hospital settings.
- **Accessibility via Telemedicine:** Addressing the barrier of clinical confinement, Russell [5] explored tele-rehabilitation through the lens of telemedicine. This research validated that remote physiotherapy programs drastically improve patient accessibility to essential services, minimize travel burdens, and lower overall healthcare costs.

III. Problem Statement

Effective knee rehabilitation requires precise movement guidance, constant physiological monitoring, and expert supervision, yet traditional therapy relies heavily on costly, time-consuming in-person hospital visits. This creates an accessibility barrier for remote patients, while unmonitored home recovery often leads to incorrect exercise execution, reduced compliance, and an increased risk of re-injury. Furthermore, without real-time tracking, clinicians cannot remotely detect pain, fatigue, or abnormal health signals during a session. To bridge these gaps, there is an urgent need for an affordable, intelligent tele-rehabilitation system that combines automated motion guidance, vital-sign monitoring, and cloud connectivity to ensure safe, accurate, and accessible knee recovery at home.

IV. Proposed System

A. System Architecture

The proposed IoT-based Knee Tele-Rehabilitation System integrates sensing, processing, actuation, and communication modules into a unified framework. A central microcontroller acquires and processes motion and physiological data, transmitting it to a cloud server for remote supervision while providing real-time feedback to the patient. An automated motor-assisted mechanism delivers controlled joint movement, ensuring safe and adaptive rehabilitation across clinical and home environments.

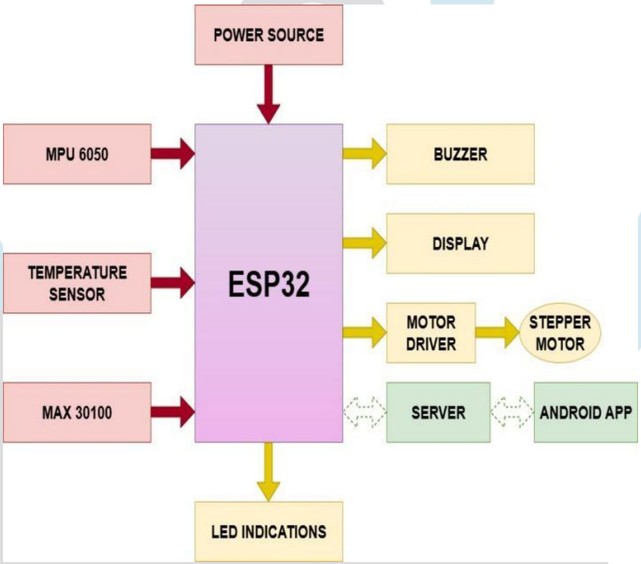

Figure 1: System Block Diagram

B. Hardware Implementation

- Processing & Connectivity: The ESP32 microcontroller acts as the central processing unit, executing control algorithms and using integrated Wi-Fi for cloud data transmission.
- Kinematic & Physiological Sensing: An MPU6050 IMU tracks real-time acceleration and gyroscopic data to evaluate range of motion (ROM). A MAX30100 sensor monitors heart rate and oxygen saturation (SpO_2), while a temperature sensor tracks knee joint thermal variations to detect inflammation.
- Actuation & Interface: A stepper motor and driver circuit provide precise, physician-configured angular control during automated therapy. A display module, LED indicators, and a buzzer provide real-time status updates and trigger multi-sensory alerts during abnormal events.

C. Software Implementation

- Firmware & Data Processing: Embedded ESP32 firmware manages real-time data acquisition, signal filtering, and threshold validation to ensure exercise accuracy and patient safety.
- User Interface & Cloud: An Android mobile application allows patients and clinicians to switch operational modes, view instructions, and configure parameters remotely. All session data is synced to a cloud server for clinical review.
- Operational Modes & Safety: The system operates in two modes:
    1. Manual Mode: The patient performs exercises independently. If the system detects incorrect execution for three consecutive attempts, it automatically switches to Automatic Mode.
    2. Automatic Mode: The stepper motor safely drives controlled joint movement based on predefined medical parameters.

V. Working Methodology

The system functions through the integration of three core operations: **continuous monitoring**, **adaptive control**, and **fail-safe supervision**.

A. Data Acquisition and Processing

The workflow initiates with real-time data collection from the patient:

- Kinematic Sensing: The MPU6050 captures raw accelerometer and gyroscope data to calculate the exact joint angle and evaluate the patient's active Range of Motion (ROM).
- Physiological Sensing: The MAX30100 tracks heart rate and oxygen saturation (SpO_2), while a dedicated thermal sensor monitors localized knee temperature to detect joint inflammation.
- Processing & Transit: The ESP32 filters these incoming signals, validates them against physician-defined thresholds, and transmits the compiled data to the cloud for clinical oversight.

B. Adaptive Control: Manual and Automatic Modes

The system dynamically balances patient autonomy with active physical assistance:

- Manual Mode: The patient independently performs exercises guided by the mobile app. The system continuously evaluates movement accuracy based on sensor data.
- Automatic Mode Transition: If the patient fails to execute the movement correctly after a preset number of attempts (indicating fatigue or restricted mobility), the system activates the stepper motor. The motor then provides smooth, controlled joint mobilization within the physician's predefined speed and angular limits.

C. Safety and Control Mechanism

To prevent overexertion or injury, a continuous safety loop runs in parallel with therapy:

Emergency Override: If the system detects any anomalous vital signs—such as tachycardia, an SpO_2 drop, or abnormal joint temperature spikes—it triggers an immediate hard stop of all motor mechanics.

Simultaneously, the system activates a buzzer and LED indicators to alert the patient. The session remains locked and will only resume once physiological parameters return to safe baseline levels.

VI. Applications

The proposed IoT-based Knee Tele-Rehabilitation System offers a versatile, scalable solution for both clinical and home-based healthcare environments. Its primary applications include:

1. Orthopedic and Post-Operative Recovery

- **Surgical Rehabilitation:** Provides guided and monitored recovery pathways following total knee arthroplasty (knee replacement), ligament reconstructions (e.g., ACL/MCL), and arthroscopic procedures.
- **Chronic and Traumatic Conditions:** Assists patients recovering from acute sports injuries, managing arthritis-related joint stiffness, or overcoming general mobility impairments.

2. Decentralized Healthcare and Telemedicine

- **Rural and Remote Physiotherapy:** Bridges the healthcare gap for patients in geographically isolated or underserved areas, eliminating the need for frequent, costly travel to specialized clinics.
- **Multi-Patient Clinical Monitoring:** Enables hospitals and rehabilitation centers to integrate the platform into existing telemedicine networks, allowing physical therapists to monitor and manage multiple patients simultaneously from a centralized dashboard.

3. Geriatric and Long-Term Care

- **Elderly Mobility Support:** Serves as an automated, safe exercise tool for aging populations requiring low-impact joint mobilization.
- **Continuous Progress Tracking:** Facilitates long-term physiotherapy programs by maintaining a comprehensive cloud-based history of recovery metrics, helping clinicians make data-driven adjustments to long-term care plans.

VII. Future Scope

Future iterations of the system will focus on incorporating machine learning techniques to analyze historical recovery trends, accurately predict patient progress, and automatically recommend personalized exercise plans based on individual performance. To provide deeper clinical insights, the integration of additional biomechanical sensors will be explored alongside the structural miniaturization of the hardware into a more portable, ergonomic wearable device. On the software side, the development of advanced cloud-based dashboards will offer clinicians enhanced data visualization for streamlined multi-patient tracking. Ultimately, this foundational architecture can be scaled and adapted to support the rehabilitation of other major joints, including the shoulder, elbow, and hip.

VIII. Conclusion

This paper presented an integrated, IoT-based knee tele-rehabilitation system that unites motion sensing, physiological tracking, and motor-assisted actuation into a single, cohesive platform. By enabling patients to perform guided exercises at home under remote clinical supervision, the system significantly improves healthcare accessibility while reducing the cost and travel burdens associated with traditional physiotherapy. Its adaptive dual-mode operation seamlessly transitions between manual and automatic assistance based on real-time performance, while the continuous safety override mechanism ensures that all therapy sessions remain within secure health limits. Overall, this cost-effective and scalable framework offers a promising, secure solution for modern decentralized orthopedic recovery.

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