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An Affordable Feedback-Driven Rehabilitation System for Home Physiotherapy Applications

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Abstract

Rehabilitation after injury or neurological disorders plays a vital role in restoring functional independence and improving quality of life. Conventional physiotherapy methods generally require continuous supervision within clinical settings, which can restrict accessibility due to factors such as cost, travel distance, and limited availability of resources. To address these challenges, this paper presents a cost-effective and user-friendly Feedback-Assisted Training System (FTS) intended for home-based physiotherapy. The proposed system delivers real-time feedback on patient movements, enabling precise execution of prescribed exercises. It incorporates affordable resistive training components, force-sensing techniques, and wireless communication modules to monitor and evaluate performance. The system is especially useful for individuals with musculoskeletal and neurological conditions, including stroke, fractures, and joint-related impairments. Furthermore, the system supports remote monitoring, allowing healthcare professionals to track patient progress and modify treatment plans as required. By improving patient participation and ensuring correct exercise performance, the proposed approach enhances the overall effectiveness of the rehabilitation process.

Keywords: *Physiotherapy, Home Rehabilitation, Feedback System, Telemonitoring, Strain Gauge, ZigBee, Embedded Systems, Motion Analysis.*

1. Introduction

Rehabilitation is fundamental in restoring physical capabilities and enhancing the overall quality of life for individuals recovering from injuries, surgical procedures, or neurological conditions. Physiotherapy interventions focus on improving mobility, muscular strength, and coordination through well-structured exercise programs. In the context of neurological rehabilitation, techniques such as Proprioceptive Neuromuscular Facilitation (PNF) and motor relearning emphasize repetitive movement training to promote neuroplasticity and functional recovery. Likewise, individuals with musculoskeletal disorders—including fractures, joint replacements, and ligament damage—require carefully guided exercises to restore normal movement patterns and functional performance. Conventionally, these therapeutic activities are carried out under the direct supervision of healthcare professionals in clinical settings. However, regular visits to hospitals or rehabilitation centers may be difficult for many patients due to factors such as travel limitations, financial constraints, and limited access to therapists. In addition, improper execution of exercises during unsupervised home practice can reduce the effectiveness of treatment. To address these limitations, there is an increasing need for cost-effective and intelligent rehabilitation systems that support home-based therapy. This study proposes a Feedback Training System that allows patients to perform exercises independently while receiving real-time corrective feedback. Furthermore, the system enables remote monitoring, thereby ensuring continuous supervision and improving the overall quality of rehabilitation care.

2. Literature Review

Recent progress in rehabilitation technology has been directed toward the development of intelligent and affordable systems that facilitate physiotherapy in home environments. Researchers have proposed various feedback-driven solutions to assist patients during unsupervised exercises while still allowing clinical monitoring. For instance, a guided Feedback Training System (FTS) was introduced to support home rehabilitation using economical hardware components combined with continuous feedback mechanisms, enabling remote supervision by

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healthcare professionals [1]. In a similar direction, a comprehensive telerehabilitation framework integrating intelligent control units, robotic assistance, and body area networks has been proposed to deliver adaptive therapy with minimal direct intervention from therapists [2]. To enhance monitoring accuracy, multi-sensor-based systems have been widely explored. Devices incorporating accelerometers, flex sensors, and force-sensitive elements have demonstrated improved capability in tracking patient movements and activity levels [3]. Wearable systems based on inertial sensors, including accelerometers, gyroscopes, and magnetometers, have also achieved precise estimation of limb position and orientation, making them suitable for upper-limb rehabilitation applications [4]. Despite these technological advancements, several challenges remain in implementing effective telerehabilitation solutions. Issues such as system reliability, regulatory compliance, and infrastructure constraints have been identified as key barriers, emphasizing the importance of robust and scalable system design [5]. Wireless body area networks (WBANs) have been introduced as a promising approach for monitoring therapy intensity, offering improved accuracy compared to conventional observational methods [6]. Further developments include internet-enabled rehabilitation platforms that support real-time interaction, motion analysis, and three-dimensional visualization, thereby enhancing the effectiveness of remote therapy [7]. In addition, inertial sensor-based motion estimation techniques have been refined using kinematic modeling and optimization strategies to achieve accurate tracking of upper limb movements [8], [9]. Machine-assisted rehabilitation has also gained attention, with studies demonstrating that robotic devices can significantly improve therapy intensity and patient recovery outcomes [10]. Wearable technologies have been highlighted for their ability to provide continuous and unobtrusive monitoring, supported by advanced data processing techniques [11]. Assistive robotic systems designed for stroke rehabilitation have shown potential in motivating patients and monitoring their activity levels during therapy sessions [12]. Moreover, telemonitoring approaches utilizing distributed software agents have enabled efficient communication between patients and healthcare providers, facilitating remote care management [13]. Motion sensor-based systems have also been employed to evaluate physical activity, contributing to improved rehabilitation effectiveness [14]. Virtual reality-based rehabilitation systems incorporating force feedback have further enhanced patient engagement by providing immersive environments along with remote monitoring capabilities [15].

3. Methodology

3.1. System Concept

The proposed Feedback Training System (FTS) is developed to support patients in carrying out physiotherapy exercises independently within a home setting, while still ensuring proper guidance and supervision. As in traditional rehabilitation practice, the physiotherapist first evaluates the patient's movement limitations and formulates a personalized exercise regimen. During the initial supervised sessions, the patient performs the prescribed exercises, and the system captures the corresponding movement data. These recorded signals are processed to establish reference movement patterns, which are stored along with the therapy plan. In subsequent home-based sessions, the patient follows these predefined patterns while performing exercises. The system continuously monitors the real-time performance and compares it with the stored reference data, providing visual feedback to help the patient identify and correct deviations.

3.2. Feedback Training System Design

The proposed FTS employs resistive components such as elastic therapy bands, which are widely adopted in physiotherapy because of their affordability, portability, and user-friendly nature. When the patient performs an exercise, the stretching of the elastic element generates a resistive force that varies with the extent of elongation.

3.3. Resistive Element Modeling

The resistive elements used in the system demonstrate non-linear stress–strain behavior, comparable to that of elastic materials such as rubber. Nevertheless, within the typical operating range of physiotherapy exercises (approximately 10–40 N), the force–elongation relationship can be reasonably approximated as linear for practical implementation.

The physiotherapist determines the suitable band length and resistance level based on the patient's required range of motion and the desired exercise intensity, ensuring that the therapy remains both safe and effective.

3.4. Force Measurement using Strain Gauge

Force generated during the exercise is measured using a strain gauge-based sensing unit. The sensor is constructed with a metallic element on which strain gauges are strategically positioned at points experiencing maximum and minimum deformation. Variations in resistance caused by mechanical strain are converted into corresponding voltage signals through a signal conditioning circuit, allowing precise force measurement. As physiotherapy exercises generally involve low-frequency movements in the range of approximately 0.2 to 2 Hz, the sensing system is specifically designed and optimized to operate effectively within this dynamic range.

3.5. Feedback Mechanism

The system delivers real-time visual feedback through a computer-based interface, where the exercise performance is presented in the form of waveform signals similar to an oscilloscope display. In this representation, the reference trajectory corresponds to the expected or ideal movement pattern, while the measured trajectory reflects the actual performance of the patient. By observing and comparing these two signals, the user can detect variations in parameters such as amplitude, execution speed, and overall motion pattern. This continuous feedback mechanism supports error correction, enhances motor learning, and contributes to more effective rehabilitation outcomes.

3.6. Exercise Implementation

The proposed system is capable of facilitating widely practiced physiotherapy exercises, including arm abduction–adduction movements and diagonal motion patterns based on Proprioceptive Neuromuscular Facilitation (PNF) techniques. The positioning of the sensing unit and the resistive element is adjusted according to the specific exercise being performed. These exercises are intended to enhance key physical attributes such as coordination, flexibility, and muscular strength, thereby contributing to improved functional recovery.

3.7. System Architecture and Data Flow

The hardware architecture of the system comprises a strain gauge-based force sensor, a signal conditioning unit (AD7796), an ATmega16 microcontroller, a ZigBee wireless communication module, and a personal computer interface. The operational sequence of the system is as follows: initially, the force applied during the exercise is detected by the strain gauge sensor. The resulting signal is then conditioned, amplified, and converted into a digital form using an analog-to-digital converter. The microcontroller processes the digitized data and prepares it for transmission. Subsequently, the processed information is sent wirelessly through the ZigBee module. Finally, the received data is displayed on the computer interface in real time, where it is also stored for further analysis.

3.8. Communication Protocol

Communication between the analog-to-digital converter (ADC) and the microcontroller is established using the Serial Peripheral Interface (SPI), which operates as a synchronous full-duplex protocol. The SPI interface consists of four primary signal lines: Master Out Slave In (MOSI), Master In Slave Out (MISO), Serial Clock (SCK), and Slave Select (SS), enabling efficient and high-speed data exchange between devices. For wireless data transmission, the system employs ZigBee technology based on the IEEE 802.15.4 standard. This communication protocol is well-suited for such applications due to its low power requirements, dependable short-range connectivity, and compatibility with distributed sensor network architectures.

4. Data Storage and Telemonitoring

The system maintains a record of exercise data for subsequent offline evaluation by therapists. This capability facilitates continuous monitoring of patient progress, supports the adjustment of rehabilitation programs when necessary, and enables remote supervision and guidance throughout the therapy process. The observations were recorded for coordinated movements involving the right foot with the right arm, as well as the right arm with the left foot. During the maximum stretch condition, the recorded voltage values ranged approximately from 2970 mV to 2989 mV for both movement

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combinations, indicating higher force application. In contrast, for movements performed up to shoulder level, the voltage values showed a slightly lower range, varying between about 2912 mV and 2964 mV. These results demonstrate a clear variation in sensor output with respect to the intensity and extent of movement, confirming the system's ability to effectively capture changes in exercise levels.

4.1. Results

The voltage variation according to the bending of the strain gauge. The voltage variation represents the change in resistance that is the force applied to the strain gauge.

Table 1 Voltage Variation According to the Bending of Strain Gauge

Vin(mv)	R1	R2	R3	Vout (mv)	Rg
5000	357	357	357	8	355.29
5000	357	357	357	7.8	355.33
5000	357	357	357	8.3	355.22
5000	357	357	357	7	355.50
5000	357	357	357	9.2	355.03
5000	357	357	357	6.9	355.52
5000	357	357	357	7.4	355.42
5000	357	357	357	8.1	355.27
5000	357	357	357	6.7	355.57

Table I presents the variation in output voltage corresponding to the bending of the strain gauge under a constant input voltage of 5000 mV. The resistances R1, R2, and R3 are maintained at a fixed value of 357 Ω throughout the observations. The recorded output voltage (Vout) exhibits slight fluctuations in the range of approximately 6.7 mV to 9.2 mV, reflecting the changes in strain experienced by the sensor. Correspondingly, the gauge resistance (Rg) shows minor variations around 355 Ω, indicating the sensitivity of the strain gauge to mechanical deformation. These results confirm that small changes in bending produce measurable variations in resistance and output voltage, demonstrating the effectiveness of the strain gauge for force sensing applications in the proposed system.

4.2. Software Simulation

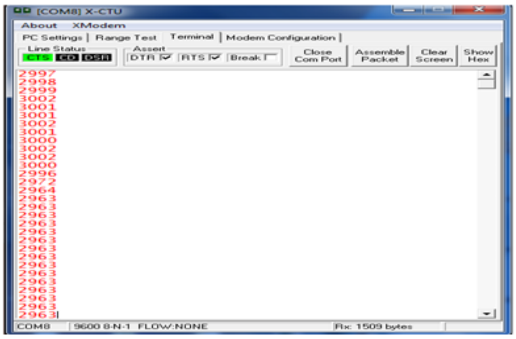

Figure 1 Simulation of ZigBee module in X-CTU software terminal

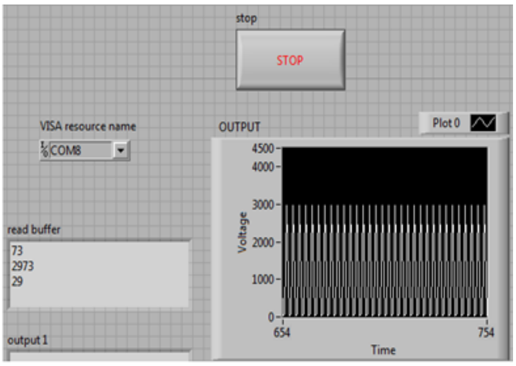

Figure 2 Simulation of ZigBee module in Lab view front panel

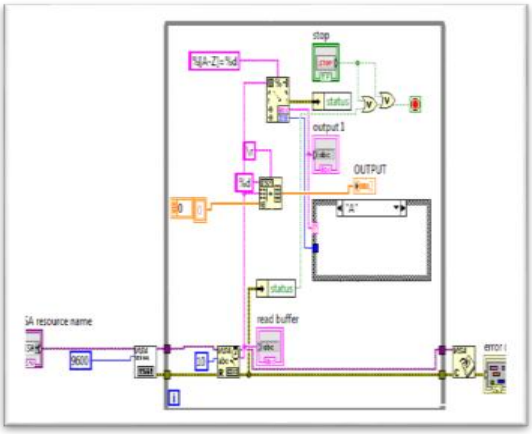

Figure 3 Simulation of ZigBee module in Lab view block diagram

Figure 1 shows the simulation of the ZigBee communication module using the X-CTU terminal, highlighting device configuration and serial data exchange between nodes. Figure 2 illustrates the LabVIEW front panel interface, which provides real-time visualization of transmitted and received data, enabling user interaction and monitoring of system performance. Figure 3 presents the LabVIEW block diagram, detailing the internal logic, data flow, and functional implementation of the ZigBee communication process within the simulation environment.

4.3. Hardware Implementation

Figure 4 depicts the initial hardware setup of the proposed system, demonstrating the integration of sensing, signal conditioning, and processing units.

Figure 4 Hardware setup 1

Figure 5 Hardware setup 2

Figure 5 shows the complete hardware configuration, emphasizing the interconnection between system components and the practical realization of the design.

Figure 6 Real time exercise monitoring without ZigBee module

Figure 6 illustrates real-time monitoring of physiotherapy exercises without the ZigBee module, where data is directly acquired and displayed, validating the core functionality of the system.

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