Tracking Knee Rehabilitation at Home Using a Smart IoT Wearable Triaxial Accelerometer

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Abstract

With the rapid progression of population aging, degenerative osteoarthritis has become one of the most prevalent conditions among older adults, leading to increasing demands for knee rehabilitation, particularly after joint degeneration and surgery. Conventional rehabilitation models are constrained by medical resources and clinical settings, making it difficult to provide long-term and real-time monitoring of exercise performance and safety. This study proposes a home-based knee rehabilitation monitoring and alert system that utilizes a wearable triaxial accelerometer to continuously acquire knee motion data, including joint range of motion, repetition counts, and holding time of each exercise. The collected signals are transmitted wirelessly to a cloud platform for data storage and analysis. Based on prescribed rehabilitation protocols and individualized safety thresholds, the system automatically identifies potential risk conditions during exercise, such as excessive joint angle, prolonged holding time, abnormal movement patterns, and unexpected interruption of training, and delivers timely alert notifications to caregivers or healthcare professionals via mobile devices. Preliminary findings indicate that, when combined with professional therapists' review and feedback, the proposed home-based rehabilitation mechanism can improve adherence to rehabilitation exercises, reduce the risk of improper movements, and support remote monitoring by clinicians. These results suggest that the system may serve as a valuable foundation for developing intelligent rehabilitation support systems and remote care services.

Keywords: Telerehabilitation, Alert mechanism, Wearable devices, Osteoarthritis, Accelerometers

1 Introduction

Osteoarthritis (OA) is a degenerative joint disease, largely driven by aging, obesity, and repetitive mechanical overuse, and is generally considered irreversible in its structural progression [1]. With advances in medical care and information technology, the global population structure is rapidly shifting toward aging. According to the United Nations World Population Prospects report, adults aged 65 years and older accounted for approximately 10% of the total world population in 2022, and this proportion is projected to increase to about 16% by 2050 [2]. In Taiwan, population projections from the National Development Council indicate that the pro-portion of adults aged 65 years and older will exceed 20% by 2025, marking the transition to a super-aged society—equivalent to one in every five citizens being 65 years or older—and is expected to surpass 30% by 2039 and approach 40% or more by 2070 [3].

Although advances in medical care have extended human life expectancy, OA remains one of the most common and representative age-related degenerative joint diseases in older adults, exerting a substantial negative impact on their quality of life and functional independence. The joints most frequently affected are those that bear higher mechanical loads, including the knees, hips, and lumbosacral spine, among which the knee joint, bearing the majority of body weight, is the most common site of osteoarthritic involvement. Current management strategies for OA primarily focus on symptom relief and functional maintenance through rehabilitation, pharmacological treatment to alleviate pain and discomfort, and, in advanced cases, total joint replacement with prosthetic implants to achieve optimal clinical outcomes [4]. However, even after joint replacement surgery, patients are required to engage in regular rehabilitation exercises to preserve joint function and must attend periodic follow-up visits for clinical assessment and monitoring.

Regular follow-up visits enable clinicians to closely monitor postoperative recovery; however, in Taiwan's healthcare context, the costs associated with postoperative rehabilitation, together with the time required to travel to rehabilitation facilities, transportation barriers, and geographic disparities in rural or remote areas, often hinder older adults from engaging in continuous and effective rehabilitation training. At the same time, shortages in human resources pose an additional challenge. For example, statistics from the American Physical Therapy Association (APTA) in 2019 indicated that there were approximately 95 physical therapists and

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39 physical therapist assistants per 100,000 population in the United States, reflecting a markedly imbalanced ratio between rehabilitation service supply and demand [5]. Rehabilitation medicine is a highly specialized and multidisciplinary field that emphasizes comprehensive interventions not only for existing impairments, problems, and diseases, but also for the prevention of potential disabilities, and involves coordinated collaboration among physiatrists, physical therapists, occupational therapists, speech-language therapists, nurses, and psychologists. Therefore, beyond developing an information system capable of tracking patients' rehabilitation status at home, reducing the workload of physical therapists while simultaneously expanding access to re-habilitation services has become an important developmental goal. In this context, the present study focus-es on physiotherapeutic rehabilitation for osteoarthritis and aims to establish a networked, digital guidance platform that enables patients to perform structured re-habilitation training in the home environment.

IoT technologies have been widely integrated into everyday life, offering users more convenient and intelligent ways of living; in parallel, the growing demand for health care has driven the emergence of medical-oriented IoT applications, including interoperability among medical devices, real-time monitoring of patients' physiological parameters, and cloud-based data processing and decision-support platforms [6]. Building on this trend, the present study adopts IoT as its core technological framework and applies it to the context of home-based knee rehabilitation. Specifically, the system leverages wireless connectivity and real-time data transmission, integrating a microcontroller, Bluetooth communication, a triaxial accelerometer, and a gravity (inertial) sensor to develop a "joint rehabilitation angle sensing system" for knee joint exercises. This system is designed to identify rehabilitation movements and quantify key behavioral parameters such as movement patterns, exerted force, and joint angles.

By exploiting the wireless and rapid pairing capabilities of IoT devices, the proposed system can be flexibly adapted to different body types and individualized re-habilitation prescriptions, thereby reducing the infra-structure and personnel costs associated with conventional rehabilitation settings and partially alleviating the shortage of rehabilitation services. The system automatically records each patient's rehabilitation history and exercise data, providing objective information to support clinical decision-making, therapeutic communication, and longitudinal follow-up between clinicians and patients. In addition, the platform offers real-time feedback on rehabilitation performance by visualizing movement accuracy and goal attainment on the user interface, together with interactive guidance to enhance patients' engagement and treatment effectiveness in the home rehabilitation environment. Furthermore, the system continuously monitors exercise execution in accordance with user behavior and prescribed protocols, issuing immediate alerts when operational difficulties or abnormal events are detected, so as to ensure training safety and timely intervention.

2 Related Work

2.1 Osteoarthritis

Osteoarthritis is one of the most common chronic diseases in middle-aged and older adults, and it most frequently affects the knee joint. Clinical and basic science studies have shown that when articular cartilage in the knee undergoes continuous wear and tear, and the regenerative capacity of chondrocytes cannot keep pace with this degeneration, progressive cartilage loss ensues; in more advanced stages, patients not only experience severe pain but may also develop marginal osteophytes (bone spurs) [7]. From the standpoint of cur-rent medical technology, osteoarthritis is essentially irreversible. In addition to pharmacological treatments such as aspirin or acetaminophen for pain and inflammation relief, and intra-articular injections of sodium hyaluronate as a lubricant and shock absorber, total knee arthroplasty (TKA) remains the most commonly performed and definitive surgical intervention. During TKA, the damaged bony surfaces are resected and re-placed with prosthetic components typically composed of metal alloys and polyethylene, which is regarded as an effective "end-stage" treatment option for advanced disease [8].

According to recommendations from the American Academy of Orthopaedic Surgeons and related professional societies, postoperative rehabilitation is a critical determinant of functional outcome after knee arthroplasty, with particular emphasis on strengthening the periarticular muscles and ligaments, maintaining or restoring maximal knee flexion range of motion, and improving muscle strength to reduce postoperative joint stiffness and abnormal load distribution, thereby promoting faster recovery and enhancing prosthetic joint stability [9]. The speed and quality of postoperative recovery are positively associated with the completeness, intensity, and continuity of rehabilitation programs, making sustained home-based rehabilitation exercises indispensable. However, in real-world practice, rehabilitation efficacy is often compromised by irregular exercise patterns and suboptimal movement quality, which may attenuate the benefits of surgery or even exacerbate discomfort. To ensure more comprehensive and consistent rehabilitation outcomes, the integration of information and communication technologies into rehabilitation monitoring and guidance has emerged as a promising strategy to support long-term, structured home exercise programs.

2.2 The Importance of Postoperative Rehabilitation Compliance

After total knee arthroplasty, in-hospital rehabilitation typically begins with the use of a continuous passive motion (CPM) device, which passively moves the knee joint through a predefined range of motion to assist early postoperative rehabilitation. The primary purpose of CPM is to help patients, who may be limited by pain and postoperative discomfort, achieve and maintain a certain degree of knee flexion and joint mobility within a safe range. While some rehabilitation movements can be assisted by CPM, the majority of knee rehabilitation exercises still rely on active participation by the patient, usually under the supervision and guidance of physical therapists or nursing staff during the hospital stay.

Once patients are discharged, physicians usually prescribe a structured home-based exercise program as part of the rehabilitation regimen. However, without the direct support of hospital-based clinicians and rehabilitation equipment, many patients experience interruptions, poor adherence, or incorrect execution of exercises in the home environment. Inadequate or insufficient postoperative rehabilitation may result in suboptimal knee flexion range of motion and residual functional limitations in daily activities, thereby compromising the overall benefits of surgery. Previous studies have shown that well-performed postoperative rehabilitation can significantly enhance recovery after knee arthroplasty [10]. Therefore, ensuring that patients continue to perform appropriate and consistent home-based rehabilitation exercises is crucial for achieving an optimal range of motion and functional outcome, making home rehabilitation a critical component of postoperative care for individuals undergoing total knee replacement.

The American Academy of Orthopaedic Surgeons has emphasized that, among the various components of postoperative care following total knee arthroplasty, structured rehabilitation exercises are of paramount importance [9]. In particular, maintaining adequate maximal knee flexion range of motion and strengthening the periarticular musculature are regarded as critical elements of the rehabilitation program. Sustained post-operative exercise not only helps reduce joint stiffness but also mitigates problems arising from abnormal muscle strength distribution, which can otherwise lead to knee instability, impaired performance in daily activities, and suboptimal functional recovery of the prosthetic joint [11].

For patients undergoing total knee replacement, early initiation and consistent execution of rehabilitation exercises are therefore essential to prevent thromboembolic complications, alleviate postoperative limb swelling, and enhance quadriceps strength, ultimately improving knee joint mobility and accelerating the restoration of joint stability. Consequently, careful monitoring and control of both the knee flexion angle achieved during home-based rehabilitation exercises and the continuity of the rehabilitation regimen are crucial for ensuring favorable long-term outcomes in this population.

2.3 Telerehabilitation

In recent years, the Internet of Things (IoT) has rap-idly permeated multiple aspects of daily life, with healthcare emerging as a major domain of application. By integrating various types of sensors with different functions and performance characteristics, IoT systems can collect diverse physiological and behavioral data from patients. In the context of rehabilitation, key indicators include precise control of joint angles, the magnitude of exerted force, and the number of exercise repetitions performed each day. Through Bluetooth wireless transmission and automatic device pairing, these data can be uploaded to cloud servers, giving rise to a new paradigm of remote rehabilitation [12].

Beyond the acquisition of accurate measurements enabled by technological intervention, the development of medical platforms has also become a critical trend. With the support of internet-based connectivity, the home environment can effectively be transformed into an extension of the rehabilitation setting. Medical platforms are capable of storing and analyzing data, transmitting processed information to the clinical team, and allowing healthcare professionals to provide timely feedback and adjust medical orders or rehabilitation prescriptions, thereby tailoring the most appropriate rehabilitation program for each patient. As a result, rehabilitation technologies and telemedicine platforms are increasingly recognized as key indicators of contemporary healthcare innovation [13].

In studies applying information technologies to support rehabilitation, Joonbum Bae and Masayoshi Tomizuka employed ground reaction force (GRF) sensors and inertial measurement units (IMUs) in gait rehabilitation. Prior to initiating rehabilitation, patients wore an “intelligent shoe” composed of these sensing components. Based on the gait data collected and fed back by the system, physical therapists were able to design appropriate rehabilitation exercise programs and modify patients’ gait patterns. The system used IMUs to compute three-dimensional kinematic and kinetic parameters during ambulation, including acceleration, magnetic field, and applied force, while GRF sensors captured reaction forces. These measurements provided detailed information on walking trajectories, step length, and walking speed. Moreover, the system incorporated a telemedicine platform, enabling clinicians to remotely and in real time monitor patients’ rehabilitation status and to deliver immediate therapeutic adjustments and preventive interventions [14].

2.4 Comparison of Alarm Push Mechanisms

In medical rehabilitation applications, commonly used IoT-based notification and alert mechanisms can be broadly categorized into in-app push notifications, short message service (SMS), email alerts, haptic or auditory cues delivered via wearable devices, and multi-channel integrated alert systems. Each mechanism presents distinct advantages and limitations in terms of timeliness, reachability, interactivity, and implementation cost, as summarized in Table 1.

3 Methodology

This study incorporates IoT devices and an information platform into the conventional rehabilitation process to propose a home-based rehabilitation service model, as illustrated in Figure 1. In traditional clinical practice, physicians typically rely on palpation and visual inspection, combined with patients’ subjective descriptions of symptoms, to determine rehabilitation plans; however, reports of pain intensity, muscle strength, range of motion, and other sensations often vary across individuals due to differences in perception and expression. Consequently, rehabilitation prescriptions and exercise intensity are frequently adjusted based on these subjective accounts. In this work, professional consultations with physical therapists were conducted to compile representative patterns of symptom–exercise combinations. For example, when the knee joint rehabilitation angle sensor detects a specific range of joint motion in the affected limb, the system can automatically suggest corresponding rehabilitation exercises. At the same time, the device provides clinicians with objective and precise quantitative data, thereby reducing discrepancies between physician and patient perceptions and enabling home-based rehabilitation behavior to be systematically measured and analyzed. The remainder of this paper focuses on the design and implementation of the networked sensing devices and the associated alert mechanisms.

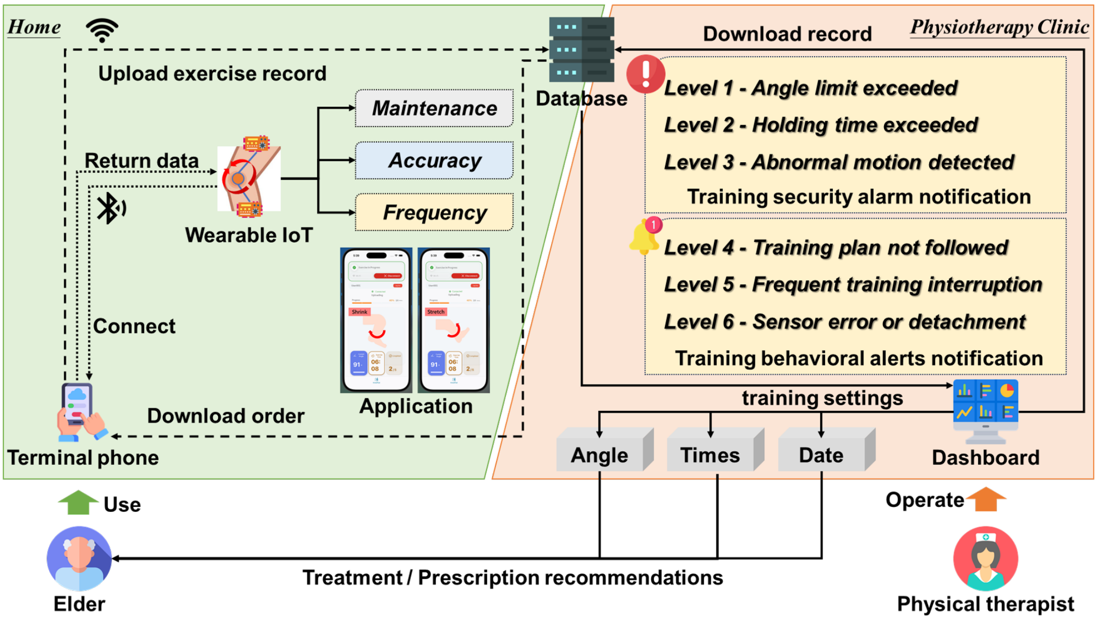

Figure 1. Research framework of an IoT–based exercise monitoring and alert service for home knee rehabilitation

Table 1. Comparison alarm mechanism

Type	Advantages	Disadvantages
App [15]	Highly customizable in terms of message content and timing.	Excessive notifications may lead to “alert fatigue.”
SMS [16]	High reachability and visibility; does not require a smartphone or app.	May incur additional costs and is limited to text-based information.
E-mail [16]	Suitable for longer text or reports; low cost and easy to integrate.	Mainly used for nonurgent, educational information; not ideal for emergencies.
IoT [17]	Provides high immediacy and real-time feedback during exercise without relying on a smartphone screen.	Often limited to vibration or simple icons, with restricted information content.
Multi-channel [18]	Can notify patients, caregivers, and medical staff simultaneously, increasing the likelihood that critical events are noticed and acted upon.	Requires integration of multiple APIs, with higher communication costs and security management complexity.

3.1 Principle of Three-Axis Acceleration Sensing

To accurately measure the angle of rehabilitation movements, we utilize a three-axis acceleration sensing component. Commonly used acceleration sensors obtain velocity and displacement information through the inertial effect of objects. The sensing unit consists of three parts: a spring, a beam, and a tether. Gravity acceleration is measured using three beams, with two beams fixed and the middle one movable. When there are changes in physical quantities of the object, acceleration and displacement occur. The data transmitted by the sensor can then be used to calculate the acceleration value. Acceleration sensing methods can be categorized as piezoelectric, capacitive, and thermal, with differences in characteristics as shown in Table 2. Since our study involves wearing the sensor during rehabilitation exercises, we consider the possibility of users experiencing increased body temperature or sweating, which may affect the sensor components. Therefore, we opt for capacitive components.

3.2 Sensing Data Communication

Based on recent advances in information and communication technologies and the expansion of IoT applications, commonly used sensing and wireless communication options include Bluetooth, Zigbee, Wi-Fi, and LoRa, as summarized in Table 3 [19-22]. In this study, the primary application scenario is the indoor home environment. Bluetooth and Zigbee offer relatively strong performance for short-range indoor data transmission and can support a higher volume of rehabilitation-related sensing data; however, their draw-backs include higher power consumption and greater costs associated with deploying multiple nodes. In addition, Bluetooth, as one of the most widely adopted short-range communication standards, is particularly suitable in this work as the main communication inter-face between the mobile device and the rehabilitation hardware.

By contrast, LoRa is designed for long-range communication and is characterized by low power consumption, low cost, and an extended communication range, typically on the order of three to five kilometers. It supports several communication modes, among which event-driven transmission can further reduce overall energy usage, and its operation in sub-GHz bands helps lower susceptibility to interference. Nonetheless, LoRa is limited by its relatively low data throughput and the fact that most households are not equipped with LoRa gateways, making it less suitable as the primary communication method for a home-based rehabilitation system. Therefore, in this study, Wi-Fi is adopted for communication between the mobile device and the cloud database/server, in order to ensure fast and reliable transmission of rehabilitation data within common home network environments. By combining Bluetooth at the device–phone layer and Wi-Fi at the phone–cloud layer, we construct an IoT communication pathway better tailored to the requirements of home-based knee rehabilitation.

Table 2. Acceleration sensing method comparison

Model	Feature
Piezoelectric	High precision, high stability, low power consumption, simple structure, and resistance to noise and temperature fluctuations. Voltage output is typically limited to applications below 125°C and can be affected by temperature and humidity.
Piezoresistive	Low impedance, excellent response, simple measurement method, but susceptible to temperature and humidity.
Capacitive	Better signal-to-noise ratio, less affected by temperature and humidity, but with a smaller signal detection range.

Table 3. Communication protocol comparison

Type	Range	Transfer volume
LoRa	5 km	50 kbps
ZigBee	less than 1 km	250 kbps
Bluetooth	100 m	2 Mbps
Wi-Fi	150 m	450 Mbps ~ 1.73Gbps
LTE	12 km	4 Mbps

3.3 Angle Calculation Mechanism

When conducting home-based rehabilitation, this study uses degenerative inflammation of the knee joint as an example and estimates the joint angle by deploying two triaxial accelerometers. The sensors are placed at the midpoints over the rectus femoris on the thigh and the tibialis anterior on the lower leg, respectively, and are aligned along the same vertical line. By comparing changes in the triaxial outputs along this common axis, the flexion angle of the knee joint can be derived and expressed as the included angle between the two sensors. When the two triaxial accelerometers tilt and form an angle, the output of the X-axis can be represented using a trigonometric function, as shown in equation (1).

$$G^X = 1G \times \sin\theta_X \quad \textbf{(1)}$$

After term transformation, equation (1) can be converted into the angle calculation formula as shown in equation (2).

$$\theta_X = \sin^{-1}\frac{G^X}{1G}, \quad \textbf{(2)}$$

Based on the two triaxial accelerometer sensors, configured as the front-end measurement module, we obtain the values G_A and G_B. When the knee joint bends during rehabilitation, the triaxial accelerometer G_A worn on the knee produces an inclination angle θ_a with respect to the horizontal axis of the thigh, while G_B produces an inclination angle G_B with respect to the horizontal axis of the thigh. By adding them together, $\theta_a + \theta_b$, we can calculate the bending angle θ_k of the knee joint.

Using this formulation, the two rehabilitation sensors are modeled with the thigh segment treated as the horizontal reference axis and the knee as the rotation center, as illustrated in Figure 2. After computing the orientation angle of each sensor, the change in knee flexion is obtained by combining (e.g., summing the relative changes of) the two angles, which yields the current knee flexion angle. This procedure and the corresponding derivation serve as the fundamental computational framework in this study and were used to conduct preliminary feasibility tests of the angle estimation method. The initial results indicate that this approach can effectively capture changes in knee angle; however, a non-negligible measurement error remains. Future work will focus on identifying the sources of error and incorporating additional variables into the model to improve computational accuracy, including refined derivations of the angle estimation equations and the integration of potential factors such as bias terms, sensor misalignment, precision calibration parameters, and dynamic acceleration during movement. Through a more comprehensive treatment of these variables, the goal is to achieve clinically acceptable precision for medical decision-making.

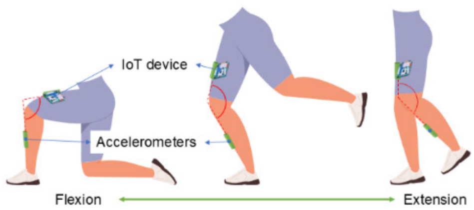

Figure 2. Knee joint sensor configuration diagram

3.4 Repetition Counting and Exercise Performance Logic

In rehabilitation, key therapeutic indicators include the standardization of movement execution, exercise intensity, and holding time; only when all elements meet the prescribed criteria can optimal therapeutic effects be achieved. In this study, the system is configured according to the physician's rehabilitation prescription and guides the patient toward clearly defined targets. Given that the device streams data in real time, a transmission interval of 3 seconds is adopted to ensure intermittent feedback and maintain a tolerable user experience.

For example, for a prescription such as "joint mobilization (30-45°, 10 repetitions, 5 second hold)," the system first instructs the patient to flex the knee to 30°, hold for 5 seconds, then extend to 45° and again hold for 5 seconds; completing this flexion–extension cycle is counted as one successful repetition. Joint angle is evaluated every 0.5 seconds. When the target angle is set to 30°, if the knee angle deviates by more than 10° within the 5 second holding period, the system determines that the posture has not been properly maintained. In parallel, to prevent overexertion, once the angle exceeds the predefined 10° deviation threshold, the front-end guidance module issues a real-time reminder and logs the event. These records allow physicians, during remote consultations, to assess the quality and consistency of patients' movements and to adjust the rehabilitation prescription accordingly.

Formally, the evaluation logic can be expressed as shown in equation (3). Let A_N denote the current joint angle, A_S the starting angle, and A_S the target angle, with C representing the angle variation between A_S and A_S , and T the timing variable. A state variable C is used to encode the progression of the movement cycle; when C changes from 0 to 2, it indicates that one complete rehabilitation repetition has been successfully performed. The default maximum acceptable angle deviation is set to 10°, but this threshold can be adjusted according to different rehabilitation prescriptions to refine the required movement standard for individual patients.

$$f(C)=\begin{cases} 0, A_S-5<A_N<A_S+5, T=5 \\ 1, A_S<A_N<A_E, \qquad T=5 \\ 2, A_E-5<A_N<A_E+5, T=5 \end{cases} \tag{3}$$

3.5 System Interface Design

The user interface (UI) is the most critical component influencing overall system experience and effectiveness. In this study, most home users are middle-aged and older adults, often with limited mobility; therefore, a simple and practical interface design is essential to reduce difficulties in actual use and to enhance user satisfaction. The interface design is based on two main principles. First, according to Cognitive Load Theory, human working memory has a limited capacity, so the interface should avoid excessive information and overly complex operations. Consequently, the system's information and functions are segmented into small, clearly defined blocks to reduce the cognitive burden on middle-aged and older users. Second, guided by Human Factors Engineering, the system is not only intended to support remote home-based rehabilitation monitoring, but also to help users understand whether their rehabilitation exercises are being performed correctly through the interface [23].

Drawing on human factors–oriented design patterns for elderly monitoring systems, the interface, as illustrated in Figure 3, provides "shrink" and "stretch" motion guidance. The system visualizes the discrepancy between the user's actual movement and the target movement, thereby offering interactive remote therapeutic guidance and educational feedback to support self-correction and learning.

Figure 3. Homecare telerehabilitation application

3.6 Alert Mechanism

In this study, the goal of the IoT-based intelligent knee rehabilitation tool is to enable users to carry out rehabilitation training anytime and anywhere. The designed alert mechanism assists older adults in adjusting or correcting their movements when improper execution is detected. The purpose of notifications is not only to "remind," but also to prevent secondary injury, ensure rehabilitation quality, enhance adherence, and support remote clinical decision-making. The alerts are categorized into six levels, which are delivered via a tiered, multi-channel notification strategy according to their severity, including real-time alerts, subsequent reminders, and notifications to the medical team, as summarized in Table 4.

Table 4. Communication protocol comparison

Level	Event	Description
I	Angle limit exceeded	Knee flexion angle exceeds the upper limit set by the physician (e.g., > 120°).
II	Holding time exceeded	Prolonged holding time
III	Abnormal motion detected	High-frequency oscillations are detected in the angle signal.
IV	Training plan not followed	No training session is performed for more than X consecutive days.
V	Frequent training interruption	Each training session is terminated before the prescribed exercises are completed.
VI	Sensor error or detachment	Angle readings remain unchanged for an extended period.

4 Results

This study developed a joint rehabilitation system for home-based telecare, enabling patients to perform rehabilitation exercises at home while maintaining continuous engagement from healthcare professionals. During each rehabilitation session, exercise data are captured by IoT devices and uploaded to a cloud database. Through the cloud platform, physicians can review patients' rehabilitation status—including training frequency, joint range of motion, and movement quality—and provide timely recommendations or adjustments to the rehabilitation program based on objective data. This section introduces the remote care system designed on the basis of the above framework, detailing its overall architecture and operational workflow.

To support effective rehabilitation exercises, we designed a knee-brace–type wearable device that integrates two ADXL-335 sensors to measure triaxial acceleration, one HC-05 Bluetooth communication module to connect with the mobile application, and an Arduino Uno control board to execute the logic and decision-making program, as illustrated in Figure 4. When the patient wears the smart knee brace and performs rehabilitationn movements, the IoT device acquires motion data and transmits them to the smartphone via Blue-tooth, where the data are received and processed by the application.

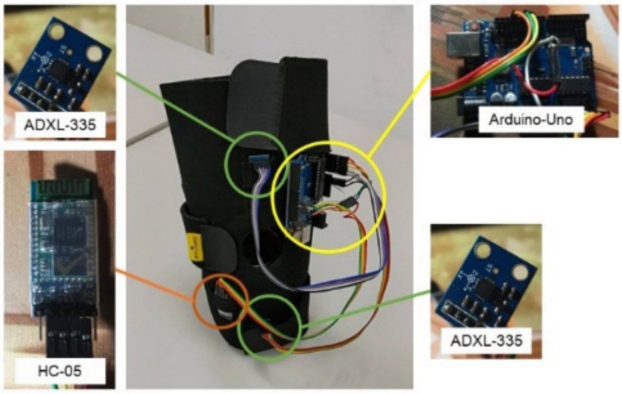

Figure 4. Wearable device introduction diagram

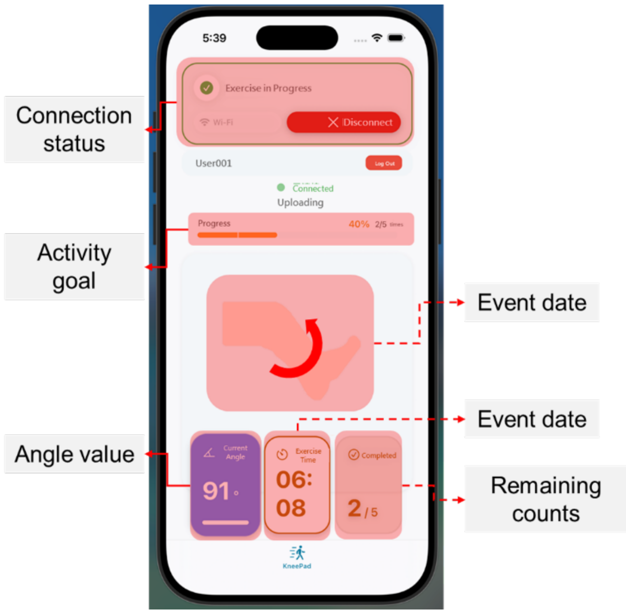

Figure 5. Home care telerehabilitation application

Once the patient has donned the IoT knee brace, they can connect it via the mobile application. The system first verifies whether the brace has been successfully paired over Bluetooth and then loads the rehabilitation prescription defined by the physician, including event parameters, the type of exercise, and the target number of repetitions or activity goals. After the user presses the start button, the system continuously acquires data from the two triaxial accelerometers embedded in the brace, computes the corresponding joint angles, and displays them in real time within the app. As described in Section 3.4, each time the patient correctly completes a prescribed movement, one repetition is deducted from the remaining count, thereby informing the patient of their progress toward completing the current rehabilitation session, as illustrated in Figure 5. To address potential difficulties that middle-aged and older adults may have in interpreting graphical instructions, a "suggestion tool" is incorporated into the interface, which provides on-screen guidance on how to correct their movements and simultaneously delivers spoken instructions, with the aim of directing users toward proper rehabilitation behavior.

From the therapist's perspective, the overall rehabilitation status of older adults is of primary concern. As outlined in Section 3.5, when an alert event is triggered, the system immediately notifies the responsible therapist and uploads the corresponding record to the cloud system. Depending on the alert level, the system can additionally determine whether the patient's family members should be notified. In the present design, the alert events are not life-threatening; therefore, the focus is on systematic recording and review rather than emergency response. As shown in Figure 6, the system inter-face for clinicians summarizes each patient's usage data—including dates, training parameters, and completion status—enabling therapists to grasp the rehabilitation situation at a glance.

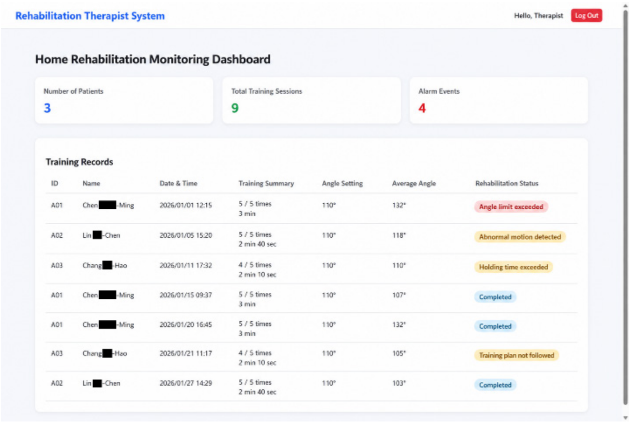

Figure 6. Home rehabilitation monitoring dashboard

5 Discussion

With the accelerating trend of global population aging, the number of older adults affected by osteoarthritis has continued to rise. Osteoarthritis is essentially an irreversible degenerative joint disorder; even after surgical interventions such as knee replacement, patients still depend on long-term, regular exercise and rehabilitation to maintain joint function and prevent further deterioration. However, frequent hospital visits for follow-up and therapy are time-consuming and physically demanding, and they pose substantial barriers for older adults with mobility limitations or those living in rural and medically underserved areas, where continuous monitoring and rehabilitation are difficult to sustain. Against this backdrop, the development of home-based telerehabilitation services has become particularly important. In this study, we employ Internet of Things (IoT) technologies to design and implement a remote knee rehabilitation assistive device that allows patients to perform prescribed exercises off-site while rehabilitation data are collected and transmitted to healthcare professionals for remote monitoring and treatment adjustment.

Osteoarthritis is an umbrella term referring to age-related degeneration of articular cartilage and associated structural and functional joint impairment. Based on consultations with rehabilitation specialists, this study focuses on the knee joint as a primary use case. The knee is one of the most commonly affected sites in osteoarthritis and plays a pivotal role in activities of daily living, including walking, toileting, sit-to-stand transitions, and maintaining an upright posture; its stability and range of motion are therefore critical to functional independence in older adults. Through this pilot system, we aim to establish rehabilitation patterns and protocols that can be extended to different osteoarthritic joints, thereby improving the effectiveness and clinical applicability of rehabilitative exercise programs.

Beyond supporting structured rehabilitation training, continuous tracking of joint motion amplitude and movement patterns in daily life is equally important. Integrating sensing components into everyday garments or wearable accessories would enable more eco-logical, real-time monitoring of older adults' mobility, allowing long-term assessment of joint loading and activity patterns. Such an approach holds promise for detecting early signs of joint degeneration before overt clinical deterioration and for informing preventive interventions and personalized rehabilitation strategies.

6 Conclusion

Rehabilitation is a highly specialized medical intervention, and in-person, one-on-one guidance delivered by trained therapists remains the gold standard of care. However, in real-world clinical settings, limitations in workforce and healthcare resources make it difficult to provide intensive, long-term supervised rehabilitation for all patients who require it. In this context, the present study adopts the concept of a remote rehabilitation system to support older adults in performing exercises independently at home, without replacing professional clinical judgment. A central objective is to assist clinicians in monitoring patients' rehabilitation performance and disease progression in a more systematic and data-driven manner. Because joint movement reflects subtle changes in muscle activation and joint mechanics, this study currently focuses on using IoT devices to capture three-axis motion signals during rehabilitation exercises and on establishing a cloud-based information platform to store and visualize these data. Future work may incorporate more advanced analytical techniques to deepen the understanding of knee joint training patterns and to explore a broader range of rehabilitation strategies.

Moreover, the design of rehabilitation programs should explicitly account for exercise resistance and loading conditions. By integrating resistance-related parameters into the system, training protocols can be better aligned with clinical practice and potentially yield greater therapeutic benefit. Another critical challenge is to enhance patients' adherence to remote rehabilitation regimens. With the rapid development of technologies such as virtual reality (VR), augmented reality (AR), computer vision, and game-based mechanics, these elements could be embedded into remote rehabilitation platforms to create more immersive and interactive training experiences, thereby increasing older adults' motivation and willingness to engage in regular exercises. As more rehabilitation data are accumulated, clinicians will be better positioned to analyze long-term patterns, refine rehabilitation models, and tailor individualized treatment prescriptions, ultimately strengthening the clinical value of telerehabilitation approaches.

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Author Contributions

All authors contributed to the study conception and design. Material preparation, data collection and analysis were performed by Syu-Bo Jhang, Jiann-Liang Chen, Shih-Yang Yang, Zong-Jie Wu and Lun-Ping Hung. The first draft of the manu-script was written by Syu-Bo Jhang and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

References

[1] A. Cui, H. Li, D. Wang, J. Zhong, Y. Chen, H. Lu, Global, Regional Prevalence, Incidence and Risk Factors of Knee Osteoarthritis in Population-Based Studies, *EClinicalMedicine*, Vol. 29-30, Article No. 100587, December, 2020. https://doi.org/10.1016/j.eclinm.2020.100587

[2] United Nations Department of Economic and Social Affairs, Population Division, *World Population Prospects 2022*, July, 2022. Available at: https://www.un.org/development/desa/pd/content/World-Population-Prospects-2022

[3] National Development Council, *Population Projections for the R.O.C.(Taiwan): 2022-2070*, 2022. Available at: https://pop-proj.ndc.gov.tw/main_en/News_Content.aspx?n=139&s=59

[4] InformedHealth.org, *Overview: Osteoarthritis*, Institute for Quality and Efficiency in Health Care, July, 2025. Available at: https://www.ncbi.nlm.nih.gov/books/NBK279589/

[5] American Physical Therapy Association, *APTA Physical Therapy Workforce Analysis*, Report, December, 2020. Available at: https://www.apta.org/contentassets/5997bfa5c8504df789fe4f1c01a717eb/apta-workforce-analysis-2020.pdf

[6] C. Huang, J. Wang, S. Wang, Y. Zhang, Internet of Medical Things: A Systematic Review, *Neurocomputing*, Vol. 557, Article No. 126719, November, 2023. https://doi.org/10.1016/j.neucom.2023.126719

[7] C. Vinatier, J. Guicheux, Cartilage Tissue Engineering: From Biomaterials and Stem Cells to Osteoarthritis Treatments, *Annals of Physical and Rehabilitation Medicine*, Vol. 59, No. 3, pp. 139-144, June, 2016. https://doi.org/10.1016/j.rehab.2016.03.002

[8] A. J. Price, A. Alvand, A. Troelsen, J. N. Katz, G. Hooper, A. Gray, A. Carr, D. Beard, Knee Replacement, *The Lancet*, Vol. 392, No. 10158, pp. 1672-1682, November, 2018. https://www.thelancet.com/journals/lancet/article/PIIS0140-6736(18)32344-4/fulltext

[9] R. H. Brophy, Y. A. Fillingham, AAOS Clinical Practice Guideline Summary: Management of Osteoarthritis of the Knee (Nonarthroplasty), Third Edition, *Journal of the American Academy of Orthopaedic Surgeons*, Vol. 30, No. 9, pp. e721-e729, May, 2022. https://doi.org/10.5435/JAAOS-D-21-01233

[10] J. J. Negus, D. P. Cawthorne, J. S. Chen, C. J. Scholes, D. A. Parker, L. M. March, Patient Outcomes Using Wii-Enhanced Rehabilitation After Total Knee Replacement: The TKR-POWER Study, *Contemporary Clinical Trials*, Vol. 40, pp. 47-53, January, 2015. https://doi.org/10.1016/j.cct.2014.11.007

[11] K. P. Iyengar, J. B. Nadkarni, N. Ivanovic, A. Mahale, Targeted Early Rehabilitation at Home After Total Hip and Knee Joint Replacement: Does It Work?, *Disability and Rehabilitation*, Vol. 29, No. 6, pp. 495-502, March, 2007. https://doi.org/10.1080/09638280600841471

[12] N. K. Suryadevara, A. Gaddam, R. K. Rayudu, S. C. Mukhopadhyay, Wireless Sensors Network Based Safe Home to Care Elderly People: Behaviour Detection, *Sensors and Actuators A: Physical*, Vol. 186, pp. 277-283, October, 2012. https://doi.org/10.1016/j.sna.2012.03.020

[13] A. Peretti, F. Amenta, S. K. Tayebati, G. Nittari, S. S. Mahdi, Telerehabilitation: Review of the State-of-the-Art and Areas of Application, *JMIR Rehabilitation and Assistive Technologies*, Vol. 4, No. 2, Article No. e7, July, 2017. https://doi.org/10.2196/rehab.7511

[14] J. Bae, M. Tomizuka, A Tele-Monitoring System for Gait Rehabilitation with an Inertial Measurement Unit and a Shoe-Type Ground Reaction Force Sensor, *Mechatronics*, Vol. 23, No. 6, pp. 646-651, September, 2013. https://doi.org/10.1016/j.mechatronics.2013.06.007

[15] A. Hernández-Reyes, F. Cámara-Martos, G. Molina Recio, R. Molina-Luque, M. Romero-Saldaña, R. Moreno Rojas, Push Notifications From a Mobile App to Improve the Body Composition of Overweight or Obese Women: Randomized Controlled Trial, *JMIR mHealth and uHealth*, Vol. 8, No. 2, Article No. e13747, February, 2020. https://doi.org/10.2196/13747

[16] A. Kulhánek, K. Lukavská, R. Gabrhelík, D. Novák, V. Burda, J. Prokop, M. Holter, H. Brendryen, Comparing Reminders Sent via SMS Text Messaging and Email for Improving Adherence to an Electronic Health Program: Randomized Controlled Trial, *JMIR mHealth and uHealth*, Vol. 10, No. 3, Article No. e31040, March, 2022. https://doi.org/10.2196/31040

[17] Z. Huang, D. McCoy, R. Cooper, T. M. Crytzer, Y. Chi, D. Ding, Wearable-Enhanced mHealth Intervention to Promote Physical Activity in Manual Wheelchair Users: Single-Group Pre-Post Feasibility Study, *JMIR Rehabilitation and Assistive Technologies*, Vol. 12, Article No. e70063, June,

2025.
https://doi.org/10.2196/70063

[18] D. Mrozek, A. Koczur, B. Małysiak-Mrozek, Fall Detection in Older Adults with Mobile IoT Devices and Machine Learning in the Cloud and on the Edge, *Information Sciences*, Vol. 537, pp. 132-147, October, 2020.
https://doi.org/10.1016/j.ins.2020.05.070

[19] E. Georgakakis, S. A. Nikolidakis, D. D. Vergados, C. Douligeris, An Analysis of Bluetooth, Zigbee and Bluetooth Low Energy and Their Use in WBANs, in: J. C. Lin, K. S. Nikita (Eds.), *Wireless Mobile Communication and Healthcare, MobiHealth 2010*, *Lecture Notes of the Institute for Computer Sciences, Social Informatics and Telecommunications Engineering, Vol. 55*, Springer, Berlin, Heidelberg, 2011, pp. 168-175.
https://doi.org/10.1007/978-3-642-20865-2_22

[20] A. C. Muhoza, E. Bergeret, C. Brdys, F. Gary, Power Consumption Reduction for IoT Devices Thanks to Edge-AI: Application to Human Activity Recognition, *Internet of Things*, Vol. 24, Article No. 100930, December, 2023.
https://doi.org/10.1016/j.iot.2023.100930

[21] E. Zanaj, G. Caso, L. De Nardis, A. Mohammadpour, Ö. Alay, M. G. Di Benedetto, Energy Efficiency in Short and Wide-Area IoT Technologies—A Survey, *Technologies*, Vol. 9, No. 1, Article No. 22, March, 2021.
https://doi.org/10.3390/technologies9010022

[22] Z. Liu, Y. Li, L. Zhao, R. Liang, P. Wang, Comparative Evaluation of the Performance of ZigBee and LoRa Wireless Networks in Building Environment, *Electronics*, Vol. 11, No. 21, Article No. 3560, November, 2022.
https://doi.org/10.3390/electronics11213560

[23] M. A. Hossain, Perspectives of Human Factors in Designing Elderly Monitoring System, *Computers in Human Behavior*, Vol. 33, pp. 63-68, April, 2014.
https://doi.org/10.1016/j.chb.2013.12.010

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