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# Concept and Development of a Real-Time Biofeedback Device for Measuring Quadriceps Lag

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## Abstract

This study presents the concept and development of a wearable, real-time biofeedback device designed to measure quadriceps lag (Q-lag) in patients undergoing rehabilitation for knee injuries. Quadriceps lag, commonly observed following anterior cruciate ligament (ACL) reconstruction or in cases of knee osteoarthritis (OA), is characterized by an individual's inability to actively achieve full knee extension despite having complete passive range of motion. Accurate and objective assessment of Q-lag is critical for monitoring recovery and guiding physiotherapy interventions; however, traditional clinical methods such as goniometry or visual estimation are often subjective, inconsistent, and not suitable for remote use. To address these limitations, a low-cost, lightweight, and portable system was developed that incorporated an MPU 6050 inertial measurement sensor and NodeMCU microcontroller to wirelessly transmit angular kinematic data to an Android application, "QuadEase." The application provides real-time visual and auditory feedback, enables setting target extension thresholds, and stores session data for tracking progress. The device was designed for both clinic and home-based rehabilitation settings. Initial testing focused on sensor calibration, appropriate anatomical placement, and user interface optimization. Informal usability trials with physiotherapists and volunteers suggested that the system is easy to use, comfortable, and provides meaningful feedback to guide neuromuscular re-education. The system offers potential for integration into post-operative and neuromuscular rehabilitation protocols, supporting patient motivation and therapist decision-making. This paper details the device's design process, mobile interface, preliminary evaluation, and its potential role in remote physiotherapy and real-time rehabilitation monitoring.

**Keywords:** Biofeedback, IMU Sensor, Knee Extension, Quadriceps Lag, Rehabilitation, Wearable Device.

## Introduction

Biofeedback therapy is a behavioural intervention that enables individuals to gain voluntary control over physiological functions by providing real-time feedback of bodily processes that are typically involuntary. Originally developed in the mid-20th century, it has become an essential component of modern rehabilitation strategies due to its ability to enhance motor control, reduce pain, and improve functional outcomes in various patient populations (1). By converting physiological signals into meaningful visual, auditory, or tactile cues, biofeedback helps patients actively participate in their recovery by modifying behaviour based on real-time information (2, 3). In physical rehabilitation, biofeedback is broadly categorized into physiological and biomechanical modalities. Physiological biofeedback includes techniques such as electromyography (EMG), heart rate variability, and respiratory monitoring, whereas biomechanical biofeedback targets posture, joint angles, force, and movement patterns (4, 5). Among these, biomechanical biofeedback has gained prominence in musculoskeletal rehabilitation due to its objective assessment capabilities and potential for remote application. With the advent of wearable technologies, biofeedback delivery has become more accessible, mobile, and patient-centric. Devices incorporating inertial measurement units (IMUs)—which typically include accelerometers and gyroscopes—can track three-dimensional joint kinematics with high accuracy (6). These wearable systems are compact, lightweight, and capable of wirelessly transmitting data to mobile devices, allowing real-time feedback that is highly conducive to both clinic-based and home-based therapy (7, 8). One specific clinical application where biofeedback shows great promise is in addressing quadriceps lag (Q-lag). Q-lag refers to the inability to actively extend the knee to its full



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passive range, often involving the final 15 degrees of extension. It is typically indicative of quadriceps muscle inhibition or neuromuscular dysfunction and is a common complication in individuals recovering from anterior cruciate ligament (ACL) reconstruction, total knee arthroplasty (TKA), or patellofemoral disorders (9, 10). Early identification and monitoring of Q-lag are critical for designing effective treatment plans and preventing long-term functional deficits. However, current methods of measuring Q-lag are limited. Tools such as the universal goniometer or visual estimation are frequently used but suffer from low inter-rater reliability and lack the precision necessary for tracking subtle improvements over time (11, 12). Advanced alternatives like motion capture systems or radiographic analysis, while more accurate, are often cost-prohibitive, non-portable, and unsuitable for repeated assessments in real-world settings (13). These challenges underscore the need for an affordable, objective, and user-friendly method of assessing knee extension—particularly a system that can support both therapist-guided and patient-led rehabilitation. Wearable biofeedback devices tailored for knee rehabilitation can address this unmet need by providing real-time angular data, facilitating patient self-monitoring, and enhancing clinician decision-making through detailed motion analytics (14, 15). Despite the growth in wearable health technologies, there remains a lack of devices explicitly designed for quadriceps lag assessment and monitoring—especially ones that combine ease of use, clinical accuracy, and cost-effectiveness.

The present study proposes the design and development of a wearable real-time biofeedback device to objectively measure quadriceps lag. The device aims to support rehabilitation by providing actionable data to both patients and clinicians, enabling precise monitoring of progress and promoting personalized recovery plans. Quadriceps lag, characterized by an individual's inability to actively extend a joint to its full passive limit, is a significant concern in rehabilitation, particularly for patients with knee injuries or disorders. Accurate assessment and real-time monitoring of quadriceps lag during rehabilitation are essential for designing effective personalized treatment plans. Currently, available measurement methods are often cumbersome, lack objectivity, and can be impractical for self-assessment by patients. There is a pressing need for a practical, cost-effective, and patient-friendly solution to address these limitations.

This study proposes a system designed to measure quadriceps lag during active knee extension in a high-sitting position, where patients are often unable to fully extend their knee to its passive limit. The approach focuses on quantifying angular deviation as a mechanical indicator of lag, rather than assessing neuromuscular activation latency. To contextualize the need for an objective and portable real-time biofeedback system, Table 1 summarizes existing approaches used in clinical and research settings to assess quadriceps lag. These methods vary in terms of technology, measurement principles, and clinical applicability. The table highlights each method's system or tool, a brief description of how it works, and its key limitations. This comparison underscores the limitations of current practices and supports the rationale for developing an improved wearable solution.

**Table 1:** Overview of Existing Methods to Assess Quadriceps Lag

| Focus Area | Method/System | Description | Limitations |
|---|---|---|---|
| Clinical Significance of Quadriceps Lag (16,17) | Not reported | Failure of active knee extension despite full passive ROM; indicates neuromuscular dysfunction | Contributes to poor function, altered gait, and delayed recovery |
| Manual Measurement (18) | Universal Goniometer | Clinician aligns arms with bony landmarks to measure joint angles | Subjective; inter-rater variability; no digital output |
| Visual Observation (19) | Functional Tests (e.g., Straight Leg Raise) | Visual estimation of lag during motion | Highly subjective; not quantifiable |
| Mobile-Based Tools (20) | Smartphone Goniometer Apps | Uses phone sensors or camera to estimate joint angles | Accuracy may vary; dependent on user skill |

| | | | |
|---|---|---|---|
| Digital Tools (21) | Electro goniometers / Inclinometers | Measures angle electronically; often used in research | Costly; not widely available in clinical settings |
| Strength-Based Estimation (22) | Isokinetic Dynamometer | Measures quadriceps strength indirectly related to lag | Measures force, not angle; not portable |
| Research-Based Motion Analysis (23) | 3D Motion Capture Systems | Infrared tracking of reflective markers to calculate joint angles | Very expensive; requires specialized lab |
| Biofeedback Systems (24,25) | EMG or IMU-Based Feedback Tools | Provide real-time visual/auditory cues during rehab exercises | Many focus on gait/balance; few directly quantify quadriceps lag |

# Methodology

## Design Philosophy

The idea of a real-time biofeedback device for evaluating quadriceps lag was driven by the principles of being portable, cost-effective, easy to use, and clinically useful. The device was designed to be lightweight and compact, allowing it to be easily attached to the lower limb with adjustable straps, making it ideal for clinical, research, and home rehabilitation environments. To facilitate easy movement and eliminate the need for complex wiring, the device used wireless data transmission through the Node MCU microcontroller, which had built-in Wi-Fi capabilities. Real-time data from the MPU 6050 sensor, which included a 3-axis gyroscope and accelerometer, is sent to a mobile device, providing instant feedback on the quadriceps lag in degrees. This feature boosts user engagement and assists physiotherapists in tracking quadriceps activation and rehabilitation progress. The graphical interface, designed for Android devices, visually displays angular movement and offers options for data recording and export. The overall flow of data collection, processing, and wireless transmission in the system is illustrated in Figure 1, showing the architecture from sensor input to mobile application output.

The design focused on cost-effectiveness by utilizing open-source hardware and free development platforms, allowing for scalability and potential replication in resource-limited settings. Furthermore, the system's modular design allows for future integration of electromyography (EMG) or bilateral sensors to enhance its research and clinical applications.

The design and development approach used continuous input from practicing physiotherapists and rehabilitation specialists with clinical expertise in addressing post-operative knee problems. Their feedback was integrated into choices on sensor placement, strap design, user interface configuration, and patient usability, ensuring the device meets actual clinical requirements.

Figure 2 shows the wearable module in action during use, highlighting its compact design, Velcro attachment mechanism, and mobility-friendly form factor.

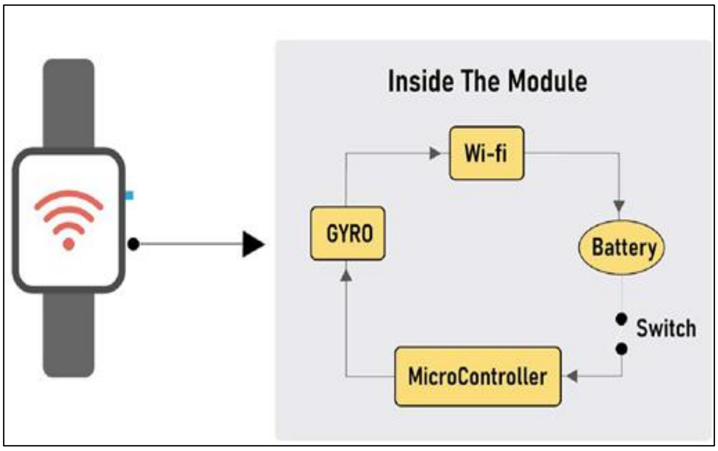


**Figure 1:** Block Diagram: System Architecture

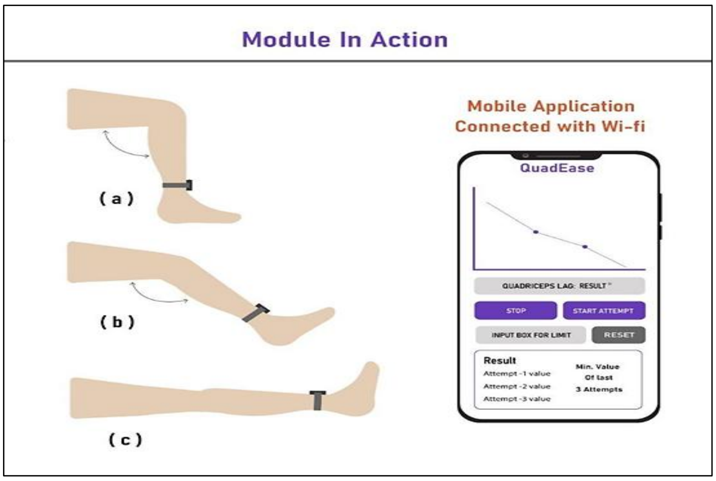


**Figure 2:** Module in Action

## Hardware Components

The proposed system incorporates four main hardware components, chosen for their compact size, functionality, and cost-effectiveness. These elements collectively create a wearable device that can accurately capture lower limb movements and transmit data in real time. Figure 3 displays the major hardware components of the system, including the NodeMCU microcontroller, MPU 6050 sensor, battery unit, and BMS, as assembled within the wearable enclosure.

**NodeMCU ESP8266 Microcontroller:** Central to the system is the NodeMCU ESP8266, a compact, low-power microcontroller with built-in Wi-Fi capabilities. Its integrated wireless communication support eliminates the need for extra modules, simplifying the circuit design while ensuring efficient data transmission. The microcontroller processes sensor data in real time and transmits the calculated values to a connected mobile interface, providing immediate visual feedback.

**MPU 6050 Motion Sensor:** The MPU 6050 is a six-degree-of-freedom (6-DoF) inertial measurement unit (IMU) that integrates a 3-axis gyroscope and a 3-axis accelerometer on a single chip. It measures angular velocity and linear acceleration, allowing for precise monitoring of knee joint movement. When positioned above the ankle or near the tibial tuberosity, the sensor captures real-time kinematic data, which is crucial for evaluating the presence and progression of quadriceps lag.

**Battery Management System (BMS):** To ensure safe and efficient power delivery, a Battery Management System is included in the device. It manages charging cycles, prevents overcharging, and regulates output voltage to protect the internal electronics. The BMS extends the battery's lifespan while ensuring uninterrupted operation during use.

**Rechargeable Lithium-Ion Battery:** The system is powered by a lightweight, rechargeable lithium-ion battery, chosen for its high energy density and long cycle life. This power source supports extended monitoring periods without frequent recharging, making the device more convenient for both clinical sessions and home-based rehabilitation programs.

All electronic components are housed within a custom-designed, 3D-printed enclosure. The casing is ergonomically shaped and lightweight, allowing it to be comfortably worn by users without hindering natural movement. Secure fastening is achieved using adjustable Velcro straps, enabling quick attachment and removal while ensuring the device remains stable during activity.

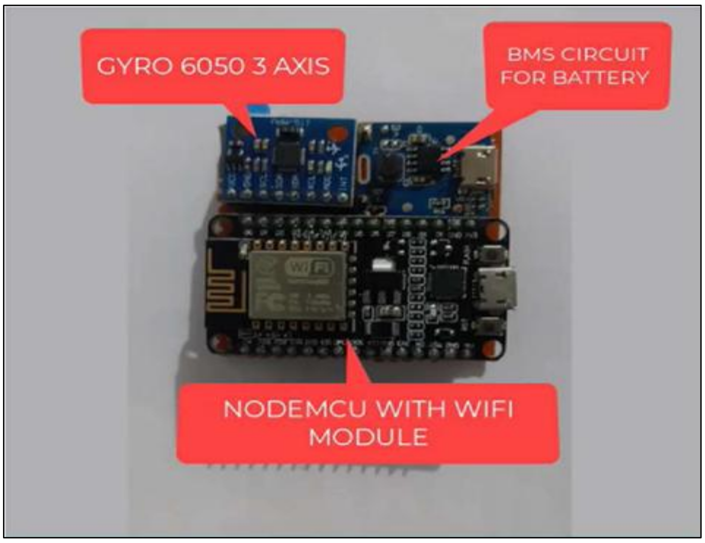


**Figure 3:** Hardware Components

## Development of Mobile Application and Its Features

After the successful development of the wearable biofeedback device, an Android mobile app called "QuadEase" was developed to connect with the hardware and offer real-time monitoring of quadriceps lag. The app features a user-friendly design and easy navigation, making it accessible for clinicians, patients, and researchers. When the app is launched, it connects to the wearable device via a wireless Wi-Fi network. Once connected, users can access a variety of interactive features designed to improve the accuracy and safety of rehabilitation protocols. An overview of the QuadEase mobile application interface is presented in Figure 4, depicting real-time graph plotting, saved session data, extension angle display, and control functions. The main features of QuadEase are described below:

**Real-time Measurements of Quadriceps Lag:** The primary function of the app is to display active knee extension and degrees of quadriceps lag in real-time. As users move their legs, the app shows angular data from the MPU 6050 sensor, providing immediate biofeedback on the degree of extension achieved. This enables therapists and patients to dynamically monitor the quadriceps lag.

**Setting Range Limits and Alert Notifications:** The app allows clinicians to set custom knee extension limits based on post-operative guidelines. For example, in the early stages after ACL reconstruction, a limit like 45° (from a 90° starting point in high sitting) can be set. When the patient reaches this limit during an exercise, an audio alert (beep) is triggered in Figure 5. This helps ensure adherence to prescribed movement boundaries and reduces the risk of overexertion or injury during recovery.

**Recording, Storing, and Reporting Data:** Each measurement session is saved in the app, tagged with a unique patient ID and date. The app securely and systematically stores angular measurements, allowing for easy tracking of rehabilitation progress over time. Additionally, session data can be exported as PDF reports, facilitating data sharing between clinicians or for inclusion in medical records and research documentation.

**Multiple Attempts and Recording of Best Value:** To enhance data reliability, three repeated measurements are taken during each session. Among these attempts, the value representing the minimum quadriceps lag is automatically selected and recorded as the final reading for the day. This approach minimizes outliers and improves the validity of the measurement used for clinical decision-making.

The integration of these features into a lightweight and mobile platform highlights QuadEase's potential to support safe, measurable, and personalized rehabilitation strategies in both clinical and home-based settings. Informal usability testing was conducted during initial trials with physiotherapists and volunteers to assess user interface clarity, device comfort, and signal response. Although not a formal validation, this feedback helped refine design features such as sensor placement, strap adjustability, and graphical interface readability.

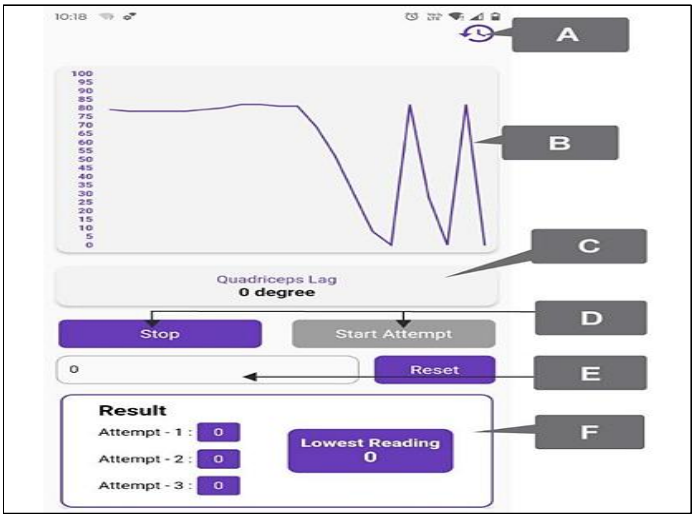


**Figure 4:** Mobile Application: A- Saved Data, B- Real Time Graph, C- Real Time Quadriceps Lag (Active Knee Extension Range of Motion in Degrees), D- Start and Stop Indicator, E- Target Limit for Active Knee Extension in Degrees, F- Result


**Figure 5:** Wearable Device and Real-Time Biofeedback Application

## Results

Initial testing of the system focused on usability, sensor calibration, and the real-time performance of the mobile application. Informal trials were conducted with physiotherapists and healthy volunteers to evaluate comfort, signal responsiveness, and interface clarity. Feedback indicated that the device was comfortable to wear, did not restrict limb movement, and provided understandable visual and auditory cues during active knee extension. The system consistently registered angular deviation corresponding to quadriceps lag when the sensor was placed correctly on the distal tibia. Real-time feedback through the QuadEase app successfully alerted users when they achieved or failed to reach preset extension targets. These findings support the system's practical feasibility and its potential for integration into clinical and home rehabilitation protocols.

Further formal validation, including reliability and clinical accuracy testing, is currently in progress and will be reported separately.

### Sensor Placement and Calibration

Accurate sensor placement was critical to ensuring reliable detection of active knee extension angles. Initially, the sensor was mounted just below the patella on the proximal tibia; however, this position failed to consistently register 0° of extension due to the anatomical curvature of the tibial tuberosity. To resolve this, the sensor was repositioned distally, approximately 5–7 cm above the ankle joint along the anterior aspect of the tibial shaft. This region provided a relatively flat, horizontal surface, allowing for precise baseline calibration and consistent readings of full extension (0°) in individuals without quadriceps lag. In this study, quadriceps lag is measured as angular deviation, specifically, the difference (in degrees) between full passive and active knee extension. For standardization, all participants were seated in a high-sitting posture on a plinth, with the knee flexed over the edge. A slight backward trunk inclination was supported by pillows to minimize hamstring-induced resistance, which could interfere with active extension. Once this posture was achieved, the sensor module—housed in the 3D-printed casing—was secured firmly using adjustable Velcro straps. The assembled wearable device, along with its integration with the real-time feedback app, is shown in Figure 5, demonstrating how the sensor is positioned and the angular output is displayed on the mobile screen during knee extension.

In the context of knee rehabilitation, quadriceps lag is defined as the difference between full passive knee extension and the maximum active extension the patient can achieve voluntarily. For the purpose of this device, the baseline was established at 0°, representing full active knee extension with the leg held straight in a horizontal position. During calibration, the sensor was aligned along the distal tibia with the participant seated in a high-sitting position and the knee fully extended. This position was considered the neutral or reference position, and the angular reading from the MPU 6050 sensor at this posture was digitally registered as 0°. Any deviation from this baseline during active movement was recorded as a positive angle, representing the presence and magnitude of quadriceps lag. For example, if a participant could only actively extend the knee to 10° short of full extension (i.e., the leg is still flexed at 10°), the application calculated and displayed this as 10° of quadriceps lag. The system ensured real-time feedback through visual graphs and numeric display, assisting both therapists and patients in monitoring and correcting movement during rehabilitation session.

## Intellectual Property

To ensure exclusive rights and safeguard innovation, the following steps were taken:

- Patent Filing: A patent application has been submitted for the hardware system under the reference number 202321030212 with the Controller General of Patents, Designs & Trademarks, India.
- Design Registration: The physical design of the device has been registered under Design No. 371386-001, with a certificate issued on 24th September 2022 by the Indian Patent Office.
- Software Copyright: The application software, Quad Ease – a mobile application for measuring quadriceps lag, has been submitted for copyright registration under Diary No. 3620/2024-CO/SW, with status "Pending for Hearing.

## Discussion

Quadriceps lag, defined as the inability to fully extend the knee actively despite passive full extension, is a frequently encountered clinical issue in patients with musculoskeletal conditions such as post-ACL reconstruction, patellofemoral pain syndrome, and knee osteoarthritis (OA). It is typically attributed to neuromuscular inhibition, pain, swelling, and reduced quadriceps strength. The significance of quadriceps weakness and afferent sensory dysfunction as central contributors to disability in knee osteoarthritis patients has been highlighted (26). Accurate and timely detection of quadriceps lag is critical for tailoring rehabilitation and preventing long-term functional impairments. Traditional assessment tools such as goniometers or visual estimation often lack precision, are prone to inter-rater variability, and offer no capacity for real-time monitoring or biofeedback. This limitation underlines the clinical need for objective, portable, and interactive tools to assess and manage quadriceps lag.

The present study outlines the conceptualization and development of a wearable real-time biofeedback system and its complementary mobile application "QuadEase." The system measures angular lag in active knee extension, typically observed when the patient, seated in high sitting, is unable to fully straighten the knee despite having passive range available. It provides an objective indicator of extension deficit relevant to rehabilitation. The system is lightweight, wireless, and easy to attach using Velcro straps, and it features a 6-axis IMU sensor (MPU 6050) and NodeMCU ESP8266 microcontroller to wirelessly transmit angular data. Upon detecting a pre-set knee extension angle—such as 45 degrees in early

ACL rehabilitation—a beep sound acts as a feedback cue, alerting the user to cease further extension. This protects against overextension while encouraging participation, making the device a potential behavioural reinforcement tool. Real-time biofeedback plays a significant role in motor learning and rehabilitation. The system's real-time auditory and visual input may be incorporated into conventional physiotherapy protocols, especially those focused on neuromuscular re-education. For example, in post-operative knee rehabilitation—such as after ACL repair or TKA—therapists may use the device to assist patients in attaining complete active extension. Immediate feedback promotes accurate movement patterns, diminishes compensatory techniques, and enhances motor learning via repetitive repetition. The capacity to establish target thresholds enables therapists to progressively increase active knee extension following recovery schedules. The effectiveness of multimodal feedback, including visual and auditory cues, in enhancing motor performance and learning retention has been emphasized (27). Our design followed this principle by combining graphical feedback through the app and auditory alerts. The ability to measure, store, and export data provides clinicians with tangible, time-stamped evidence of patient progress—an advancement over traditional methods that rely heavily on subjective observation and patient reporting. While formal usability and comfort assessments are planned in follow-up studies, preliminary feedback from pilot participants indicated that the device was generally comfortable to wear, the mobile interface was intuitive, and the real-time audio-visual feedback was well understood and easy to respond to. Additionally, the inclusion of multiple attempts for measuring quadriceps lag and adopting the lowest value from the trials as the representative measurement reflects a commitment to accuracy and clinical pragmatism. Similar approaches have been validated in range of motion studies, where repeated measures have been shown to reduce random error and enhance reliability (10).

Recent literature also supports the integration of wearable sensor systems into rehabilitation. It has been confirmed that inertial measurement units (IMUs) provide accurate joint angle data when properly calibrated and positioned (28). It has been demonstrated that smartphone-based feedback systems significantly enhance adherence and clinical outcomes in home-based rehabilitation (29). The QuadEase system is consistent with these developments, offering real-time feedback and data capture while also facilitating patient autonomy and motivation, a factor that has been identified as significantly affecting outcomes in rehabilitation adherence studies (30). From a clinical application standpoint, this system is particularly suited for early post-operative ACL rehab, knee OA management, and neuro-rehabilitation where quadriceps activation and monitoring are essential. Moreover, its lightweight, wireless, and mobile-compatible design supports its integration into tele-rehabilitation, as has been highlighted in recent studies on tele-rehabilitation and virtual physiotherapy platforms (31). At present, the manuscript focuses solely on the design and development phase of the device. Validation studies on the system's reliability and clinical accuracy are in progress and will be reported separately. Nonetheless, preliminary internal tests have shown promising consistency and user satisfaction.

In conclusion, this novel device bridges a major clinical gap by offering a robust, cost-effective, and user-centric solution for real-time quadriceps lag monitoring. With future validation and software refinements, it holds significant promise for mainstream use in clinics, research, and remote rehabilitation platforms.

This study primarily addresses the conceptualization, hardware-software integration, and usability aspects of the biofeedback device. Formal reliability and validity data are not included in this report and will be disseminated following the completion of on-going evaluation studies. Until these metrics are published, the system should be considered as a prototype pending clinical standardization.

## Conclusion

This study presents the design and development of a novel wearable biofeedback system tailored for real-time measurement of quadriceps lag. By integrating a six-axis IMU sensor with wireless data transmission and a user-friendly mobile application, the system offers an accessible, cost-effective, and clinically useful solution for monitoring active knee extension deficits. The inclusion of features such as real-time feedback, preset movement thresholds, session data storage, and report generation enhances its potential for both clinical practice and home-based rehabilitation.

Initial performance testing confirmed the system's usability, consistency, and relevance for physiotherapy applications. The ability to provide immediate feedback and objective angular measurements makes this system an important tool in supporting neuromuscular re-education, promoting adherence, and guiding recovery in patients with knee impairments. Although this report focuses on the conceptual and developmental aspects of the device, formal validation studies are currently underway to establish its reliability, clinical accuracy, and effectiveness in real-world rehabilitation settings. With further refinement and validation, this device may be integrated into routine care protocols and tele-rehabilitation platforms, ultimately supporting safe, personalized, and measurable recovery strategies for individuals with quadriceps dysfunction.

## Abbreviations

ACL: Anterior Cruciate Ligament, BMS: Battery Management System, EMG: Electromyography, IMU: Inertial Measurement Unit, IOT: Internet of Things, IRB: Institutional Review Board, MPU: Microprocessor Unit, OA: Osteoarthritis, PCB: Printed Circuit Board, Q-lag: Quadriceps Lag, ROM: Range of Motion, TKA: Total Knee Arthroplasty, Wi-Fi: Wireless Fidelity.

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## Author Contributions

SK: Conceptualization, device design, mobile application development, manuscript drafting, figure preparation, AKS: Technical supervision, critical review of the manuscript, guidance in methodology, final manuscript approval.

## Conflict of Interest

The authors do not have any potential conflicts of interest with respect to this manuscript.

## Ethics Approval

The study received ethical approval from the Marwadi University Ethics Committee (MUEC/2022/02) with registration number ERC/356/Indt/GJ/2022, recognized by the Central Drug Standard Control Organization (CDSCO), Government of India.

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