Gamified VR-Based Therapy System for Upper Limb Rehabilitation in Children with Hemiplegia.

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Draft Proposal Report

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1. DECLARATION

We declare that this is our own work and this proposal does not incorporate without acknowledgement any material previously submitted for a degree or diploma in any other university or Institute of higher learning and to the best of our knowledge and belief it does not contain any material previously published or written by another person except where the acknowledgement is made in the text.

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Abstract

Upper limb hemiplegia in children, often resulting from cerebral palsy or pediatric stroke, significantly impairs motor function and independence. Effective rehabilitation requires intensive, repetitive, and engaging therapy to promote neuroplasticity. However, traditional therapy methods are frequently monotonous, leading to poor adherence, while access to consistent clinical supervision is limited, especially in resource-constrained settings like Sri Lanka. Current solutions are often prohibitively expensive, focus solely on distal limbs (hand/wrist), or lack real-time, automated feedback on movement quality.

This research proposes the design and development of a gamified Virtual Reality (VR) therapy system to address these challenges. The system leverages low-cost wearable Inertial Measurement Unit (IMU) sensors to track shoulder, elbow, wrist, and finger movements in real-time. A machine learning model, specifically a Long Short-Term Memory (LSTM) network, is trained to classify movements as "correct" or "compensatory" (e.g., shoulder hiking), providing objective quality assessment. This analysis is integrated into an immersive VR game environment, built with Unreal Engine, where a child's avatar mirrors their movements. The gamified therapy provides engaging, goal-oriented exercises and delivers immediate corrective feedback based on movement quality.

Preliminary results from a proof-of-concept focusing on shoulder movement demonstrate the feasibility of the sensor integration and classification approach. The proposed system aims to increase patient motivation and adherence through gamification, enable effective home-based rehabilitation, and provide therapists with quantitative data to track progress. By offering a scalable, affordable, and clinically valid solution, Handy Play has the potential to significantly improve upper limb rehabilitation outcomes for children with hemiplegia in Sri Lanka and beyond.

Keywords: *Pediatric Rehabilitation, Hemiplegia, Virtual Reality, Gamification, Wearable Sensors, Machine Learning, Upper Limb, Tele-rehabilitation, Sri Lanka*

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2. Introduction

Upper limb rehabilitation is a critical component of treatment for children with hemiplegia, a condition often resulting from cerebral palsy or pediatric stroke that causes paralysis or severe weakness on one side of the body [1]. Regaining motor function is essential for performing activities of daily living and achieving independence. Clinical evidence strongly supports that early, intensive, and consistent rehabilitation can harness neuroplasticity to help restore function [2]. However, the practical implementation of this therapy faces significant barriers.

In practice, access to regular, supervised therapy is severely limited. This is especially true in countries like Sri Lanka, where the availability of therapists is scarce, travel to clinics is costly, and adherence to prescribed regimens is low due to the repetitive and often monotonous nature of traditional exercises [3], [4]. This gap between clinical need and practical delivery results in suboptimal outcomes for a large number of children.

Technology-assisted rehabilitation has emerged as a promising solution to these challenges. Research shows that gamified rehabilitation and Virtual Reality (VR) can be key innovations to increase user engagement and improve the accuracy of movement practice [5], [6]. By transforming therapeutic exercises into immersive and enjoyable game-like activities, these systems can motivate children to adhere to the high number of repetitions required for meaningful recovery [7].

However, a review of existing systems reveals significant limitations. Many commercial solutions are designed primarily for adults and are often prohibitively expensive [8]. Others rely on complicated robotic hardware or tethered motion capture systems that are unsuitable for home or widespread clinical use [9], [10]. Crucially, many systems focus exclusively on the hand and wrist, ignoring the proximal joints of the shoulder and elbow which are fundamental to coordinated arm movement [11]. Perhaps the most critical shortfall is that most systems provide feedback on task completion but lack the ability to automatically assess the quality of movement, failing to detect and correct compensatory patterns that can hinder recovery [12].

This research proposes to address these limitations through the development of a comprehensive, gamified VR-based therapy system for upper limb rehabilitation in children with hemiplegia. The proposed system, Handy Play will utilize low-cost, wearable sensors to track the entire upper limb. A core innovation is the integration of a machine learning model to classify movement quality in real-time, providing immediate feedback within an immersive VR environment. This approach aims to make effective, engaging, and clinically valid rehabilitation accessible for home and clinical use in Sri Lanka, ultimately aiming to improve functional outcomes and quality of life for children with hemiplegia.

3. Background

Upper limb hemiplegia in children, a condition characterized by paralysis or significant motor impairment on one side of the body, is most caused by congenital brain injuries such as cerebral palsy (CP) or acquired events like pediatric stroke [1]. In Sri Lanka, the prevalence of cerebral palsy is a significant concern, with an estimated 3-5 children per 1000 live births affected, translating to thousands of children nationwide living with this condition and its associated motor disabilities [2, 3]. This motor impairment severely impacts a child's ability to perform essential Activities of Daily Living (ADL) such as feeding, dressing, and grasping objects fundamentally affecting their independence, social participation, and overall quality of life [4].

The cornerstone of effective neurorehabilitation is intensive, repetitive, and task-specific movement training, which leverages the principle of neuroplasticity the brain's remarkable ability to reorganize itself by forming new neural connections throughout life [5]. For children with hemiplegia, this means that consistent practice of targeted upper limb exercises can help reroute motor commands around damaged neural pathways, leading to improved motor function and control [6].

However, the practical implementation of this ideal therapy regimen in Sri Lanka faces two formidable barriers: limited access and poor adherence.

- Limited Access: Sri Lanka experiences a critical shortage of trained pediatric physiotherapists and occupational therapists, a gap that is acutely felt in rural areas outside major urban centers like Colombo [7]. The centralization of specialist services means that families often face prohibitive travel costs and time commitments to access consistent clinical supervision. This results in therapy sessions being infrequent and short-lived, falling far short of the intensive repetition required for meaningful neuroplastic change [8].
- Poor Adherence: Traditional home-based exercise programs are often monotonous and lack engagement, failing to sustain the motivation of children. This leads to frustration, boredom, and ultimately, poor adherence to prescribed therapy routines [9]. Without the guiding presence of a therapist, children often develop and reinforce compensatory movement patterns such as hiking the shoulder or flexing the trunk to move a weakened arm which are inefficient and can lead to long-term musculoskeletal complications, ultimately hindering functional recovery [10].

Technology-assisted rehabilitation has emerged as a powerful tool to overcome these challenges. Virtual Reality (VR) and gamification have shown immense potential in transforming repetitive exercises into immersive, engaging, and motivating experiences for children [11]. Studies by researchers like Liao et al. demonstrate that VR serious games can significantly increase motivation and adherence to therapy by providing an environment where children are focused on play rather than exercise [12].

Concurrently, advancements in affordable sensor technology, particularly Inertial Measurement Units (IMUs) like the MPU-6050, have made precise motion capture accessible outside high-end laboratories [13]. These low-cost, wearable sensors can accurately track joint angles and movement kinematics, providing the objective data necessary to monitor rehabilitation progress remotely [14].

However, a significant gap remains in existing solutions. Many engaging VR systems rely on controllers that track only hand movement, ignoring the critical biomechanics of the shoulder and elbow where compensatory patterns originate [15]. Conversely, sophisticated sensor-based systems that can capture this data are often designed for offline clinical assessment rather than providing real-time, intelligently generated feedback within an engaging game environment for the user [16].

Therefore, there is a pressing need for an integrated solution that synthesizes these technological strands a system that is not only engaging and accessible but also clinically intelligent. This project aims to bridge this gap by developing a low-cost, gamified VR rehabilitation system that uses wearable IMU sensors to capture full upper limb kinematics and employs machine learning to provide real-time, automated feedback on movement quality, specifically designed for home-based use for children with hemiplegia in Sri Lanka.

4. Literature Review

The development of effective and accessible rehabilitation tools for children with hemiplegic cerebral palsy is a significant challenge, particularly in resource-constrained settings like Sri Lanka. This review synthesizes existing research across four key domains: (1) Virtual Reality (VR) for engagement, (2) wearable sensor technology for motion tracking, (3) automated movement quality assessment, and (4) the specific technological constraints and opportunities in developing regions. The goal is to identify the critical gap that this research aims to fill: a low-cost, integrated system that provides real-time, intelligent feedback on movement quality within an engaging VR environment.

4.1. Virtual Reality and Gamification in Motor Rehabilitation

A primary obstacle in pediatric rehabilitation is maintaining patient engagement through repetitive exercises. Research has consistently shown that VR and gamification are powerful tools to overcome this monotony. Studies by Liao et al. [1] and Bortone et al. [2] demonstrate that immersive VR environments can significantly increase motivation and adherence in children. Liao et al. [1] developed VR serious games with activities like "Fishing" and "Whac-a-Mole" to encourage specific arm movements, reporting high levels of user enjoyment. Furthermore, Aloraini et al. [3] highlight the efficacy of motor imagery and action observation principles naturally embedded in VR systems where an avatar mirrors the user's movements in enhancing neuroplasticity and motor recovery.

However, a critical limitation of many existing VR systems is their reliance on commercial controllers (e.g., Oculus Touch) or computer vision, which often tracks only the hand or controller itself. This approach fails to capture the kinematics of the entire upper limb, missing crucial data on compensatory strategies at the shoulder and elbow, which are common in hemiplegia [4]. These systems prioritize task completion over movement quality.

4.2. Wearable Sensors for Motion Capture

Inertial Measurement Units (IMUs) have emerged as a low-cost, portable alternative for precise motion capture. The MPU-6050 sensor, as detailed by Liu et al. [5], is a cornerstone in this domain. It integrates a 3-axis accelerometer, a 3-axis gyroscope, and a Digital Motion Processor (DMP) in a single chip, enabling accurate tracking of orientation and movement. Liu et al. successfully used this sensor to classify shoulder motions with 94% accuracy using an XGBoost model, proving its efficacy in capturing complex joint movements [5]. This validates the MPU-6050 as a viable, low-cost sensor for our specific application, directly addressing its availability in the Sri Lankan market.

Beyond single joints, Jung et al. [6] demonstrated a more comprehensive approach using a network of five IMU sensors to monitor reaching exercises in stroke survivors. Their work confirms that data from wearable sensors can be used to objectively quantify movement. However, their system was designed for clinical assessment in adults, not for integrated, real-time feedback within a gamified environment for children.

4.3. Automated Assessment of Movement Quality

The goal of rehabilitation is not just movement, but correct movement. Compensatory strategies, such as excessive trunk flexion or shoulder hiking, can hinder long-term recovery if not corrected [7]. Traditionally, quality assessment relies on subjective therapist observation. Recent research has focused on automating this process using machine learning (ML).

The work by Jung et al. [6] is again pivotal, as they showed that an ML model could estimate a therapist's quality score with high accuracy (ROC Area = 0.91) using only the first 5 seconds of IMU data. Liu et al. [5] further demonstrated the suitability of the XGBoost algorithm for classifying kinematic data from IMUs. These studies lay the methodological foundation for our project. The identified gap is that this powerful analytical capability is rarely integrated back into the user's experience in real-time to guide and correct movement during exercise.

4.4. The Imperative for Low-Cost, Integrated Solutions in Developing Regions

High-end solutions like robotic exoskeletons [8] or integrated FES systems [9] exist but are prohibitively expensive and complex for widespread use in countries like Sri Lanka. This creates a disparity in access to advanced rehabilitation technology. Therefore, there is a compelling need for research that focuses not just on technological advancement, but on appropriate technology designing systems that are affordable, maintainable, and effective within specific socio-economic constraints.

Table 1:Sysnthesis of Literature and Identification of the Research Gap

Research Focus	Key Strengths	Key Limitations	Relevance to Our Project
VR for Engagement	High motivation, improved adherence, leverages neuroplasticity.	Often tracks only hand/controller; misses proximal compensation; no quality feedback.	Provides the model for an engaging interface. We extend it by driving the VR avatar with full-limb IMU data.
Wearable Sensors	Low-cost, portable, provides objective kinematic data (acceleration, angular velocity).	Often used for offline assessment only; not fully integrated with real-time feedback loops.	MPU-6050 is our chosen sensor. We use its data for both VR control and ML analysis.
Movement Quality	Enables automated, objective assessment of movement strategies.	Lacks real-time integration into a therapeutic game for immediate user feedback.	We use XGBoost/ML models to analyze IMU data in real-time to assess movement quality.

High-end Systems	High precision and power assistance for severe cases.	Extremely high cost, not portable, unsuitable for home or resource-limited settings.	Highlights the gap our project addresses: creating an accessible alternative.
Our integrated System	Low-cost, engages children, tracks full limb, provides real-time quality feedback, designed for home use.		This project synthesizes the strengths of the above to address their collective limitations.

4.5. Conclusion

The current landscape of upper limb rehabilitation technology is bifurcated: engaging VR systems lack biomechanical intelligence, while sophisticated sensor-based systems lack integration and real-time feedback for the user. There is a pronounced lack of solutions that are simultaneously effective, engaging, affordable, and designed for the developing world.

This project directly addresses this gap. By leveraging the proven capabilities of the low-cost MPU-6050 sensor [5] and machine learning models like XGBoost, we aim to build upon the work of Jung et al. [6] and Liu et al. [5] to create a unified system. This system will integrate full-limb motion capture into an engaging VR game and close the loop by providing the child with immediate, intelligently generated feedback on their movement quality, offering a comprehensive, accessible, and effective rehabilitation tool for children with hemiplegia in Sri Lanka and beyond.

5. Research Gap

The comprehensive review of existing literature reveals significant advancements in individual components of upper-limb rehabilitation technology. However, a critical void remains in the integration of these components into a cohesive, practical, and accessible system tailored for pediatric home-based therapy, particularly in resource-conscious environments.

As established, VR and gamified systems demonstrate high efficacy in user engagement and motivation [1], [2]. Concurrently, the feasibility of using low-cost IMU sensors, specifically the MPU-6050, for accurate motion capture and classification has been successfully proven [3]. Furthermore, machine learning models, including XGBoost, have shown exceptional promise in automating the assessment of movement quality from kinematic data [3], [4].

Despite these individual strengths, current systems fail to synthesize them effectively. VR applications often rely on controllers or computer vision that neglect proximal joint kinematics, thus ignoring the critical assessment of compensatory strategies [5]. While sophisticated wearable systems can capture this data, they are primarily designed for offline clinical assessment in adults and lack integration into a real-time, engaging feedback loop for children [4]. High-fidelity solutions, such as robotic exoskeletons and integrated FES systems, remain economically prohibitive for widespread deployment in contexts like Sri Lanka [6], [7].

Therefore, the identified research gap is the absence of a low-cost, integrated rehabilitation system that provides real-time, intelligent feedback on movement quality within an immersive and motivating VR environment for children with hemiplegia.

- **The Integration Gap**: No system seamlessly merges full upper-limb kinematic tracking via low-cost IMUs with an immersive VR game environment controlled by the user's natural movements.
- **The Feedback Gap**: Existing wearable sensor systems focus on monitoring and assessment but fail to translate their analytical output into immediate, intuitive, and corrective feedback for the user during exercise.

- **The Accessibility Gap**: Advanced solutions are often engineered for well-funded clinical settings in developed countries, ignoring the socio-economic constraints of developing nations, where cost and portability are paramount.
- **The Pediatric Design Gap**: Many technical solutions are designed for and tested on adult stroke populations, lacking the design principles, engagement strategies, and movement models appropriate for children with cerebral palsy.

This project is designed to bridge this gap by developing a system that leverages the specific capabilities of the MPU-6050 sensor [3] and XGBoost model for classification [3], [8] to drive a VR-based serious game that not only encourages repetition but also provides real-time feedback on movement quality, offering a comprehensive, affordable, and effective therapeutic tool for home use.

6. Research Problem

The core research problem addressed in this study is the lack of accessible, engaging, and intelligent rehabilitation tools that can provide real-time feedback on movement quality for children with upper-limb motor impairments, such as hemiplegic cerebral palsy, in resource-constrained settings. This overarching problem can be broken down into several key technical and practical challenges:

- **The Inaccessibility of High-Fidelity Rehabilitation Technology**

Existing solutions that provide precise motion analysis and guided therapy, such as robotic exoskeletons and laboratory-grade motion capture systems, are prohibitively expensive, complex to operate, and confined to well-funded clinical settings. This creates a significant barrier to access for patients in developing countries and rural areas, and limits the frequency and duration of therapy sessions, which is critical for neuroplasticity and recovery.

- **The Engagement Gap in Repetitive Therapy**

Conventional home-based exercise programs are often monotonous and fail to maintain the long-term engagement and motivation necessary for children to adhere to the high number of repetitions required for effective motor recovery. While commercial video games and some VR systems improve engagement, they typically focus on task completion (e.g., hitting a target) using controllers, rather than on the quality of the movement itself, often ignoring harmful compensatory strategies.

- **The Lack of Automated, Real-Time Quality Assessment**

The assessment of movement quality specifically, the identification of compensatory strategies like trunk flexion or shoulder hiking is currently reliant on the subjective, observational analysis of a trained therapist. This makes it impossible to provide immediate corrective feedback during home exercise. There is a critical absence of integrated systems that can automate this assessment using affordable sensors and artificial intelligence, and then deliver the analysis back to the user in real-time.

- **The Technical Challenge of Integrating Components into a Cohesive System**

While individual technologies exist (e.g., IMU sensors for tracking, machine learning for classification, VR for immersion), they operate in isolation. A significant problem is the technical integration of these components into a single, low-latency, and reliable system. This involves the seamless pipeline from raw sensor data acquisition and processing, to real-time machine learning inference, to the translation of that inference into meaningful and intuitive feedback within an immersive game environment.

7. Objectives

7.1. Main Objectives

The main objective of this research is to design, develop, and validate a low-cost, gamified upper-limb rehabilitation system that uses inertial sensors and machine learning to provide real-time feedback on movement quality for children with hemiplegia.

7.2. Specific Objectives

7.2.1. To design and implement a robust hardware and software pipeline for capturing and processing full upper-limb kinematics.

- Details: This involves selecting and configuring the MPU-6050 IMU sensors, developing firmware for the microcontroller (ESP32) to read raw sensor data, and establishing a stable wireless (e.g., Bluetooth or Websocket) or wired data transmission protocol to a PC. The software will include algorithms for converting raw sensor data into calibrated orientation quaternions or Euler angles, and fusing accelerometer and gyroscope data using a complementary or Kalman filter to achieve accurate and drift-free positional tracking of the shoulder and elbow joints.

7.2.2. To develop a machine learning model capable of automatically classifying movement quality and identifying compensatory strategies in real-time.

- Details: This objective involves designing a data collection protocol to gather labeled kinematic data from both typical and compensatory movements. Features such as joint angles, angular velocities, and movement smoothness will be extracted from the processed IMU data. An XGBoost model (or similar) will be trained on this dataset to classify movements as "correct" or "compensatory" (e.g., trunk flexion, shoulder hiking) with a target accuracy of >90%, as established in prior literature [3]. The model will be optimized for low latency to enable real-time inference during gameplay.

7.2.3. To engineer an immersive and motivating Unity-based VR game that is directly controlled by the user's authentic arm movements.

- Details: This involves creating a 3D game environment in Unity. The player's avatar will be animated in real-time using the data from the IMU sensors, ensuring a natural and intuitive control scheme that requires proper shoulder and elbow movement to interact with the game world. The game mechanics (e.g., reaching, grabbing, throwing) will be designed in consultation with occupational therapists to target specific therapeutic goals and ranges of motion relevant to hemiplegia.

7.2.4. To design and integrate a real-time, multi-modal feedback system within the game environment to guide the user toward correct movement patterns.

- Details: This is the core innovative objective. The output from the ML model (Objective 2) will be used to generate immediate feedback within the game. This will not be a simple "right/wrong" signal but an intuitive, integrated guide. Modalities will include:
- Visual: The game avatar demonstrates the correct movement path; highlighting the compensating body part (e.g., the trunk turning red if it leans too far).
- Auditory: Distinctive, non-punitive sound cues that change in pitch or tone based on movement quality.
- Gamified: The game's scoring mechanism will be directly tied to movement quality, not just task completion. Higher scores and rewards are unlocked for movements that minimize compensation.

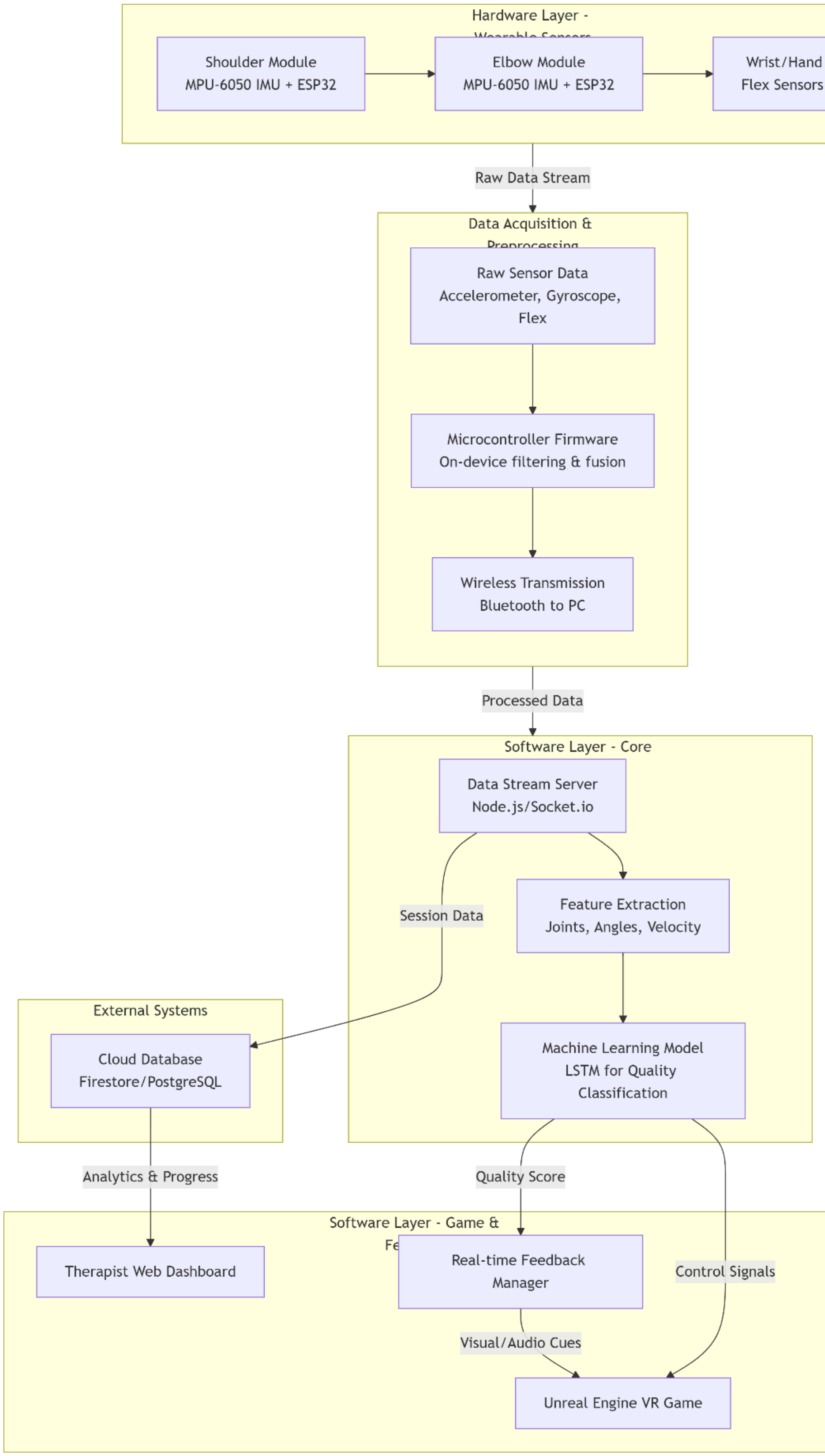
7.2.5. To evaluate the integrated system's usability, engagement, and technical efficacy through a pilot study with target users.

- Details: This objective involves conducting a small-scale user study to validate the system. Metrics will include:
- Technical Performance: System latency, tracking accuracy, and ML model performance in a real-world setting.
- Usability: Measured via standardized scales like the System Usability Scale (SUS).
- User Engagement: Observed through session duration, user effort, and qualitative feedback from children and therapists.

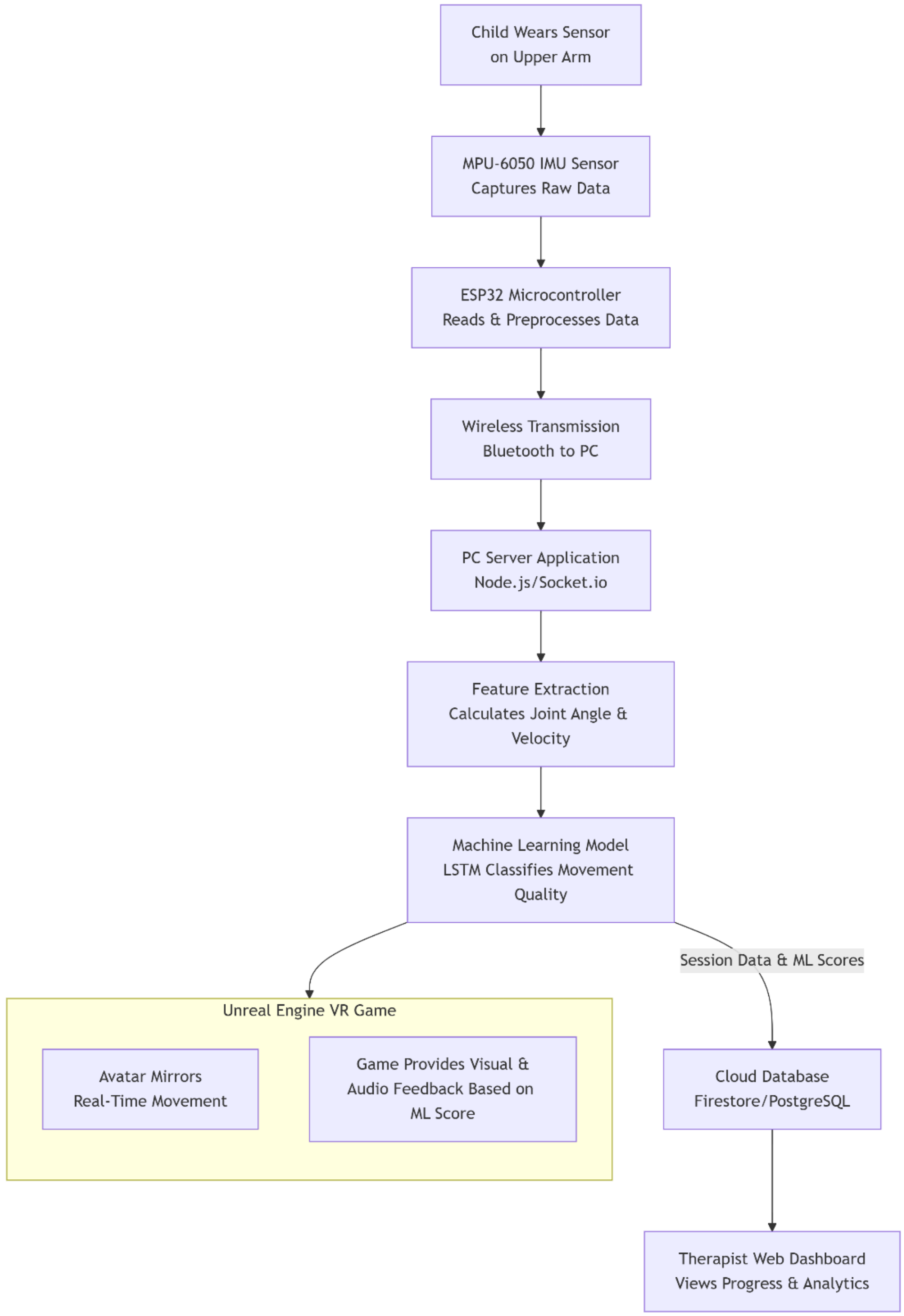
8. Methodology

The proposed system follows a structured, component-based methodology to ensure technical robustness and clinical relevance. This section details the development process for the shoulder movement tracking and gaming component, which is responsible for capturing proximal upper limb kinematics and integrating them into the therapeutic game environment. The process is divided into four key stages: hardware design, data collection & preprocessing, machine learning model development, and VR game integration.

8.1. System Overview



8.2. Component Overview



8.3. Methodology Used

8.3.1. Sensor Selection and Hardware Design for Shoulder Tracking

The foundation of the shoulder component is a wearable sensor module designed to accurately capture the kinematics of the shoulder joint, which is fundamental for reach and grasp movements often impaired in hemiplegia [4, 5]. An Inertial Measurement Unit (MPU-6050) is selected due to its low cost, availability, and integration of a 3-axis accelerometer and a 3-axis gyroscope, which are essential for calculating orientation [5, 7]. This makes it ideal for deployment in resource-constrained settings like Sri Lanka.

The MPU-6050 sensor will be securely mounted on the upper arm of the child's affected limb using an adjustable, child-friendly strap, ensuring comfort and consistent positioning across sessions. For data acquisition and transmission, an ESP32 microcontroller is chosen for its integrated Bluetooth connectivity, processing capabilities, and affordability, facilitating seamless wireless communication with the game PC [9].

The sensor setup will be calibrated for each child. Static calibration will define the neutral shoulder position (arm at rest by the side), while dynamic calibration will involve guiding the child through a range of motions (flexion, extension, abduction) to establish personalized baseline angles and minimize sensor drift.

8.3.2. Data Collection and Preprocessing for Shoulder Movement Classification

Data collection is crucial for training a robust machine learning model to classify movement quality. Initially, a benchmark dataset will be created by recording shoulder movement data from healthy children performing standardized actions such as shoulder flexion-extension and abduction-adduction. This establishes a normative model of "correct" movement patterns [5, 6].

Following this, data will be collected from children with hemiplegia. Crucially, the system will first identify the child's capabilities by using a simple "mirroring game" in the VR environment.

This game will ask the child to mimic the avatar's movements with their unaffected arm. The data from this session will personalize the system's understanding of the child's maximum range of motion and typical movement patterns, allowing it to tailor difficulty and feedback for the affected arm [4].

Raw sensor data (accelerometer and gyroscope readings) are inherently noisy. A sensor fusion algorithm, such as a complementary filter or Kalman filter, will be implemented on the ESP32 to combine these readings into stable estimates of pitch and roll angles, which correspond to primary shoulder movements [5, 7]. This processed orientation data will then be wirelessly streamed to the game engine. Feature extraction will focus on kinematic parameters such as joint angle, angular velocity, and movement smoothness, which are known to differentiate compensatory from correct movements [5, 6].

8.3.3. Machine Learning Model Development for Shoulder Movement Assessment

The goal of the ML model is to automatically classify shoulder movements in real-time as "correct" or "compensatory" (e.g., shoulder hiking or excessive trunk flexion). A Long Short-Term Memory (LSTM) network is chosen as the classifier for this component due to its proven effectiveness in modeling time-series data, such as the sequence of movements captured by the IMU [4, 5].

The labeled dataset (from healthy and hemiplegic children) will be split into training, validation, and testing sets. The model will be trained to identify the features associated with compensatory patterns. For real-time deployment within the Unreal Engine game, the trained model will be optimized and converted to a format compatible with the engine (e.g., using ONNX Runtime). This allows for low-latency inference, ensuring that feedback is delivered immediately during gameplay without disrupting the user experience [5, 7].

8.3.4. VR Game Integration and Real-Time Feedback for Shoulder Therapy

The shoulder rehabilitation exercises are embedded into an immersive VR game environment developed in Unreal Engine using C++. The player's avatar will be animated in real-time using the orientation data streamed from the ESP32, creating a direct "embodied mirroring" effect that enhances engagement and motor learning [2, 4].

The game mechanics will be designed around shoulder movements. For example, a game scenario might require the child to control a bird's wings (through shoulder abduction/adduction) to fly or move a shield (through flexion/extension) to block projectiles. The real-time output from the LSTM classification model will be integrated to provide multi-modal feedback:

- Visual: The game avatar will demonstrate the correct movement path. If compensation is detected (e.g., shoulder hiking), the avatar's trunk might glow red.
- Auditory: Distinctive sound cues will indicate the quality of the movement—a positive sound for correct form and a neutral, corrective sound for compensation.
- Gamified: Scoring will be directly tied to movement quality. Higher points and rewards are unlocked for repetitions performed with minimal compensatory patterns, incentivizing correct movement rather than just task completion [1, 4, 5].

This closed-loop system ensures that the game is not just a motivating environment but also an active therapeutic tool that guides the child toward correct movement patterns.

8.4. Technologies

The successful implementation of the proposed shoulder rehabilitation system relies on a carefully designed, multi-layered technology stack. Each layer is chosen for its affordability, effectiveness, and suitability for deployment in low-resource environments, ensuring the system is both clinically relevant and technically robust.

Hardware Layer

The hardware foundation for the shoulder component is built upon the ESP32 microcontroller, selected for its integrated Bluetooth Low Energy (BLE) connectivity, processing capabilities, and low cost, making it ideal for real-time biomedical applications [1]. The ESP32 interfaces with the MPU-6050 Inertial Measurement Unit (IMU), a low-cost, reliable sensor that combines a 3-axis accelerometer and a 3-axis gyroscope, essential for capturing shoulder kinematics [2]. The sensor is mounted on an adjustable, child-friendly strap for secure placement on the upper arm. Power is supplied via a standard USB power bank, ensuring safety and ease of replacement for home use.

Firmware and Data Handling Layer

The firmware for the ESP32 is developed using the Arduino IDE (C++), a lightweight and widely-supported platform ideal for embedded systems prototyping [1]. This firmware handles critical tasks: reading raw data from the MPU-6050, implementing a sensor fusion algorithm (such as a complementary or Kalman filter) to compute stable shoulder orientation angles, and packaging this data for low-latency transmission to the PC via BLE [3]. This on-device processing is essential for reducing noise and providing a clean data stream.

Machine Learning Layer

Machine learning is pivotal for the automated assessment of movement quality. A Long Short-Term Memory (LSTM) network is employed for this task due to its proven efficacy in classifying time-series movement data and identifying compensatory patterns like shoulder hiking [3], [4]. The model is trained in Python using TensorFlow on a curated dataset of labeled shoulder movements. For real-time deployment within the game engine, the trained model is optimized and converted using ONNX Runtime, ensuring high-performance, low-latency inference without compromising the user experience [5].

Game Development Layer

The immersive therapeutic experience is delivered through a VR game developed in Unreal Engine 5 using C++. Unreal Engine is chosen for its high-fidelity graphics, robust physics engine, and strong support for VR development, which are crucial for maintaining user engagement and presence [6]. The engine receives real-time shoulder angle data to drive the avatar's movements, creating an accurate embodied mirroring effect. The game logic integrates the output from the ML model to provide immediate visual and auditory feedback based on movement quality.

Data Communication Layer

A Node.js server application running on the host PC acts as the central communication hub. It uses the Socket.io library to establish a stable WebSocket connection for receiving data from the ESP32 via BLE. This server simultaneously broadcasts the data to multiple clients: the Unreal Engine application for avatar control and a Python service for ML inference, ensuring perfect synchronization between the physical movement and the virtual environment.

Cloud and Monitoring Layer

Google Firebase Fire store serves as the cloud database, providing a scalable, secure, and real-time solution for storing session data, including raw kinematics, ML quality scores, and performance metrics [7]. This enables remote monitoring and longitudinal progress tracking. A secure React.js-based web dashboard allows therapists to log in, view analytics, and adjust patient therapy plans remotely, which is vital for overcoming geographical barriers to care in Sri Lanka [8].

9. Requirements

The proposed shoulder rehabilitation component with sensor-driven functionality aims to accurately capture, analyze, and provide feedback on shoulder movements for children with hemiplegia. To ensure its therapeutic effectiveness, technical robustness, and user safety, defining clear and comprehensive requirements is crucial. These requirements are categorized into the following primary groups.

9.1. Functional Requirements

Shoulder Movement Tracking

- The system shall capture raw accelerometer and gyroscope data from the MPU-6050 IMU sensor placed on the user's upper arm.
- The embedded firmware on the ESP32 shall perform sensor fusion (e.g., via a complementary filter) to convert raw data into stable shoulder pitch and roll angles.
- The system shall transmit processed joint angle data wirelessly to the host PC via Bluetooth with a minimum frequency of 30 Hz to ensure real-time responsiveness.

Movement Quality Assessment

- The system shall extract kinematic features (e.g., angular velocity, range of motion, movement jerk) from the stream of shoulder angles.
- The machine learning model (LSTM) shall classify shoulder movements in real-time as "correct" or "compensatory" (e.g., shoulder hiking, trunk leaning).
- The system shall calculate a quantitative movement quality score for each repetition based on the ML classification confidence and extracted features.

Real-time feedback integration

- The system shall map the user's real shoulder angles to the virtual avatar's shoulder joint in Unreal Engine with a latency of less than 200 milliseconds.
- The VR game shall provide immediate visual feedback (e.g., avatar demonstration, color changes) based on the ML model's output.

- The VR game shall provide immediate auditory feedback (e.g., positive sounds for correct form, neutral cues for errors) based on the movement quality score.
- The game's scoring mechanism shall be based primarily on movement quality, not just task completion.

9.2. Non-Functional Requirements

Performance

- The data pipeline from sensor data capture to avatar movement in VR must operate with an end-to-end latency of less than 300 ms to maintain immersion and provide timely feedback.
- The ML model must perform inference (classification) on a stream of data in real-time, requiring a processing time of less than 50 ms per analysis window.

Usability

- The wearable sensor strap must be adjustable and comfortable for children aged 5-12 to wear for sessions of up to 30 minutes.
- The system setup (turning on sensors, connecting to PC) must be achievable by a parent or therapist in less than 5 steps.

Reliability

- The Bluetooth connection between the ESP32 and the PC must maintain a stable connection with less than 5% data packet loss during a 30-minute session.
- The system must be able to recover from a lost connection and resume data streaming without requiring a full restart.

Safety

- The hardware design must be entirely low-voltage and battery-operated, posing no electrical risk to the child.

- All components must be securely fastened to the strap to prevent choking hazards or components coming loose during use.

Cost-Efficiency

- The total Bill of Materials (BOM) for the shoulder module (ESP32, MPU-6050, wiring, strap) must remain under LKR 5,000 to ensure affordability and scalability in the Sri Lankan context.

9.3. User requirements

Therapist Requirement

- Therapists must be able to view a historical log of a child's shoulder movement quality scores over time.
- Therapists must be able to set personalized movement angle thresholds for each child based on their initial assessment.
- Therapists must be able to remotely select which shoulder-focused games or exercises are assigned to a child.

Child/Parent Requirement

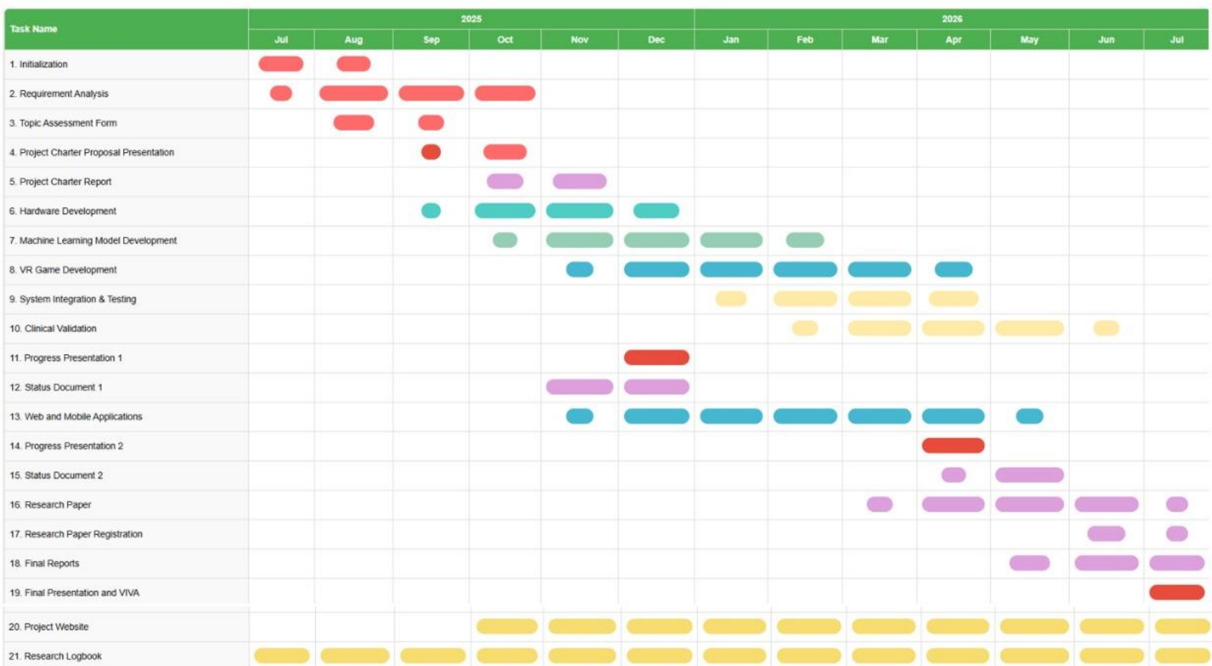
- The child must be able to understand the connection between their real-world movement and the avatar's movement in the game.
- The child must be able to put on the sensor strap with minimal assistance.
- The parent must be able to start a therapy session by launching the game on the PC and powering on the sensor.
- The parent must receive a simple summary report after a session (e.g., "Time exercised: 20 min," "Good movements: 85%").

10. Commercialization

11. Research Planning and Timeline

11.1. Planning

11.2. Work Breakdown Structure



11.3. Gantt Chart

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13. Appendix