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

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Draft Proposal Report

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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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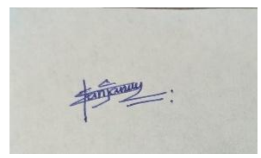
Nimesh S D S	IT2102546	

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Abstract

Hemiplegia in children with perinatal stroke, traumatic brain injury, or cerebral palsy results in significant impairment of upper limb function and fine motor skills. Trouble with grasping, pinching, extending, releasing, and coordinated tapping directly, which limit independence in daily activities and impact aspects of a child's social or emotional well-being. Traditional rehabilitation offers standardized guided therapeutic exercises, which include a good amount of success, but it can be seriously limited in places with low resource settings such as Sri Lanka for many reasons, including the limiting-scale of available therapists, affordability, distance traveled to therapy, and client compliance due to repetitive nature of basic therapeutic exercises.

This proposal introduces a low-cost and technology-driven rehabilitation platform that combines wearable flex-sensor gloves, machine learning (SVM, LSTM), and a gamified virtual reality (VR) environment. The platform captures all of the children's finger muscles in real-time with flex-sensor gloves, with those movements classified into six functional categories, then associated with prescribed therapeutic movement during the narrative of a VR game entitled, "Magic Quest: The Enchanted Fingers". As children participate in the magical adventure, they perform prescribed therapeutic exercises to cast spells, open runes, and unlock enchanted treasures Rehabilitation will never be so much fun and motivating

A multi-tiered support ecosystem expands the potential of the platform. Clinicians can monitor a child progress, prescribing modifications and providing feedback at any moment; parents can monitor therapy adherence and outcomes using the caregiver dashboard; and an AI voice assistant will provide consistent encouragement when clinical monitoring cannot be applied. The system sustains engagement with adaptive difficulty scaling, real time feedback, audiovisual and visual representations.

By transforming the traditional model of clinical rehabilitation into gamified immersive therapy with the technology of remote media, it captures key barriers that limit care in pediatric hemiplegia, accessibility, motivation and continuity of care. The technology has the potential to improve a child's motor recovery therapy adherence and emotional well-being in a scalable way in low resource health care settings.

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1. Introduction

Hemiplegia, frequently due to perinatal stroke, traumatic brain injury, or cerebral palsy, is a neurological condition that presents with weakness or paralysis on one side of the body. A common and significant consequence is the loss of upper limb use and fine finger action. Children with hemiplegia are affected by lower-level motor skills such as grasping, pinching, extending, releasing, and coordinated tapping, essential in the acquisition of independence in everyday life. This lack of ability translates to lack of independence or ability to complete activities of daily living - using utensils, moving or opening objects, writing, buttoning clothing, playing with peers, etc. As a result, hemiplegia impacts more than just the physical development of children; it also impacts the child's cognitive, social, and emotional development, frequently resulting in frustration, lowered self-esteem, and returned reliance on caregivers [1].

Standard therapy, mainly physiotherapy and occupational therapy, continue to be the standard intervention for improving motor recovery. Rehabilitative approaches aim to build muscles and coordination and, through repeated task-focused exercises, retrain neural pathways. There is a volume of evidence backing conventional therapy as an improved outcome for children; however, in the lower-resourced context of Sri Lanka and other countries, children are often limited in access to regular and high-quality therapy [2]. Some of the barriers to minimize this gap are detailed below.Shortage of trained pediatric therapists, particularly in rural areas.

- There is a limited number of pediatric-trained therapists, particularly in rural locations.
- The costs associated with long-term rehabilitation make it unobtainable to many families.
- Infrequent visits to specialized care locations are hampered by geography and public transportation for kids.
- Traditional exercises are monotonous, which reduces motivation and compliance in children who are easily distracted in environments that are comfortably stimulating/playing [3].

These challenges highlight the urgent need for innovative, affordable, and engaging rehabilitation solutions that can be deployed both at clinical centers and in home environments.

Recently, wearable and virtual reality (VR) technologies have made strides toward rehabilitation therapies to help people recover and learn specific movements. Wearable systems, and especially gloves with flex sensors, can provide instant measures of the joints of the fingers during rehabilitation. In general, these sensors represent the six base categories of finger movement: flexion and extension, abduction and adduction, pinching, grasping, releasing, and tight tapping. These movements form the basis of functional hand activities [4], [5]. Furthermore, wearable systems allow for tracking quantitative measures of motor activity as opposed to observational therapy, allowing therapists and caregivers to view changes in motor ability over time using standard measures.

In addition to sensor based technology, machine learning (ML) has provided a method for interpretation of complex motion signals. Algorithms such as Support Vector Machines (SVM) work well for recognizing static gestures, however, the Long Short-Term Memory (LSTM) neural network was developed for identifying motion in sequential patterns over time. By rapidly classifying movement according to class without human intervention, ML allows for an individualized therapy program that is based on the child's own motor and learning capabilities and recovery path. Importantly, studies have demonstrated that the benefits of wearable sensing, combined with ML, increases precision, adaptiveness, and attentiveness to rehabilitation protocols [6], [7].While sensing and classification provide the foundation, sustaining a child's motivation during therapy is equally important. Traditional repetitive tasks are often demotivating, but when integrated into gamified virtual reality experiences, rehabilitation becomes immersive, enjoyable, and rewarding. VR-based games have been shown to increase adherence, extend practice time, and improve emotional engagement, all of which are critical for long-term recovery [8].

Extending this idea, this project will demonstrate a low-cost wearable glove system utilized with machine learning (ML) models (SVM and LSTM) and an engaging VR game environment. The proposed system, unlike simple task-based games, incorporates therapy into the engaging narrative fiction of the game (called "Magic Quest: The Enchanted Fingers"). In this adventure, children become a young wizard restoring magic to a kingdom by tracing and performing therapeutic finger motions through the use of a glove interface. Each hand motion directly relates to a magical game action:

- Extending fingers - casting fire or shield spells.
- Pinching - lighting up magical crystals.
- Grasping and releasing - opening enchanted treasure chests.
- Sequential tapping - unlocking mystical runes.
- Abduction/adduction - channeling beams of magical energy.

This site visits to meaningful in-game achievements through therapeutic exercises that produce salient audiovisual feedback (e.g. glowing effects, fireworks, cheering sounds, and responsive magical creatures effects) when successful movements are performed, promoting progress and maintaining high levels of engagement.

To ensure that the individualization component of the mapping is met, the system first collects baseline data from healthy children to inform their normative movement ranges. For hemiplegic children, the unaffected upper extremity acts as an internal standard to direct and promote rehabilitation of the affected hand. The VR game also automatically adapts to different levels of difficulty through adaptive scaling, adjusting task difficulty based on the child's engagement and progress. For example, if the child shows increased strength and precision, the game will then transition to increased tapping speed or encourage holding a grasp for a longer time; if the system begins to find signs of fatigue or frustration, the level of intensity will decrease so that therapy remains challenging but not overwhelming [9].

The platform also reaches beyond gameplay, with a multi-layered support network that includes doctors, parents, and AI. All performance data is automatically uploaded to a secure monitoring platform available to clinicians. Doctors have access to the patient's progress over time, quality of movement, and they can remotely assign new therapeutic targets. If available, the doctor may also directly interact with the patient via the integrated assistant interface, to change exercises, or to provide prompts and encouragement. If the doctor is not available, a voice assistant built into VR will provide motivational prompts, narrate in playful ways, and provide positive reinforcement to keep the patient engaged. Parents likewise have a role in the intervention: using a caregiver dashboard, they can study progress metrics, monitor compliance, and encourage subsequent practice. Together with the supervision of the doctor, the willingness of the parents to engage, and the availability for AI assistance for reminders, engaging support devices bridges many of the gaps due to limited health care resources in Sri Lanka, so that therapy is ongoing, supervised, and socio-emotionally supported [10].

To conclude, the system overviewed combines wearable flexible sensor technology, machine learning gesture recognition, and virtual reality-based gamified rehabilitation into one minimal cost platform for hemiplegic children in rehabilitative therapy. By wrapping clinical therapy in a magical adventure and placing the child amongst a supportive ecosystem of doctors, parents, and intelligent assistants the project aims to mitigate the downsides of standard therapy namely access, adherence, and motivation. It is believed that this may have a significant impact on pediatric rehabilitation for impoverished rehabilitation settings not only restoring locomotor function to a child, but also restoring their self-confidence, independence, and joy to life.

2. Background

For collecting data, the ESP32 microcontroller was selected for its low-cost, compact form factor, and built-in Wi-Fi and Bluetooth connectivity, which makes communication with virtual reality (VR) platforms seamless. Sensor calibration involves a two-step process; static calibration that sets the zero and maximum bending locations, then dynamic calibration that logs bend positions for limb angles within personalized motion baselines. The glove does not use a battery solution as this adds costs and risks, instead is powered through the ESP32 board, which alone is plugged into a breadboard power supply. Male-female jumper wires connected the components providing stability during prototyping and clinical evaluations. Again, this setup can be run continuously and safely at home or clinical environments without relying on rechargeable batteries.

Hand and finger function are pivotal to achieving independence and being able to complete basic Activities of Daily Living (ADL's) i.e., grasping, writing, dressing, and manipulation [1], [2]. In children with hemiplegia, their ability to execute the respective fine motor functions is restricted due to weakness on one side of their body, lack of dexterity, and abnormal movement [1], [2]. When these children are unable to participate fully in common daily activities this not only inhibits their engagement, but can also have broader implications concerning their esteem, performance at school, and social integration.

Traditionally, rehabilitation in this area often involves task-specific and repetitive practice to help improve motor coordination and strength in hemiplegic children [3]. However, upper-limb rehabilitation is also complicated by ensuring sufficient intensity of therapy, and adherence to home programs. In Sri Lanka, pediatric occupational therapy specialists are still scarce and community or home-based therapy typically engages poorly, with participants showing poor compliance [2], [3]. Consequently, many children will not have the opportunity to engage in enough practice to maintain neural control and consequently drive neuroplastic reorganization.

Recent developments in the fields of Virtual Reality (VR) and serious gaming provide promising avenues for replacing traditional rehabilitation with immersive, motivating, and child-centered experiences. Rehabilitation interventions using VR have been found to improve therapy adherence, and increase motor outcomes by embedding exercises within a fun and goal-oriented context [3], [8], [9]. Liao et al. [4] reported that VR serious games prolong attention and engagement, while Brunner et al. [8] found that pediatric motor rehabilitation was superior when therapy was gamified. However, the majority of commercially available VR systems employ controllers, and resume screen and ignore fine finger-level kinematics and joint motion and focus only on gross maneuvers of the arm.

Wearable sensor-based technologies, especially flex-sensor gloves provide a viable and inexpensive alternative to capture finger motions [7]. Flex-sensor gloves can capture whole motor sequences including: flexion/extension, abduction/adduction, pinching, grasping, and releasing; these actions are specifically linked to ADLs [7]. The benefit of a glove compared to vision-based systems, is that gloves withstand conditions in the home-related environment because occlusion levels are decreased, making a glove feasible for addressing long-term use and low-resource contexts [7].

The raw motion data produced by these gloves can also be further enriched via machine learning (ML) techniques so they may support some level of intelligent gesture recognition and movement quality. Machine learning approaches including Support Vector Machines (SVM) to account for static gestures and Long Short-Term Memory (LSTM) networks, to analyze sequential gestures, have been shown to accurately classify hand movements and associated compensatory strategies at relatively high accuracy [6], [7]. Huang et al. [7] note how ML-based approaches improve classification accuracy and allow for tailoring rehabilitation therapy, an important consideration when considering interventions with pediatric clients.

Lastly, maintaining persistent motivation throughout therapy is a practically imperative aspect of pediatric rehabilitation. Across the literature there are consistent themes indicating that gamification strategies, including rewards, adjustable levels of challenge, and play narrative, have been shown to improve adherence to therapy [9], [11]. Sardi et al. [11] describe how gamified systems can positively influence engagement, while Lewis et al. [10] emphasize the value of parents in supporting self- guided practice. By incorporating opportunities for motivational feedback by way of animations, sounds, and rewards systems into therapy environments, the duration and quality of engagement can be improved [1], [9].

In summary, while VR, wearable gloves, ML, and gamification have all been shown to have high potential for pediatric rehabilitation, the existing solutions are fragmented. Most systems either focus on engagement or on assessment, but without biomechanical intelligence and without providing real-time video games with a rewarding game-based experience. This project fills this gap in the market with a low cost, gamified VR rehabilitation system called Magic Quest: The Enchanted Fingers, which combines flex-sensor gloves with

ML-based gesture recognition software and includes a tri-layered support/health-care model that involves (therapist, parent, AI) effective, accessible, and motivating rehabilitation for hemiplegic children while living in Sri Lanka.

3. Literature Survey

3.1. Clinical context and rehabilitation requirements

Children with hemiplegia experience unilateral motor impairment, often characterized by weakness, impaired dexterity and impaired bimanual use [1], [2]. Evidence suggests that conventional therapy is effective in achieving positive rehabilitation outcomes, but in countries like Sri Lanka, access to therapy is limited due to a shortage of pediatric therapists, costs, and access to therapy services [2], [3]. Therefore, alternatives for rehabilitation that are low-cost, accessible, and interesting must be created.

3.2. Virtual reality (VR) and serious games for rehabilitation

VR-based rehabilitation has been recognized as a new and promising way to provide pediatric motor training. Evidence suggests that VR and serious games can promote engagement, motivation, adherence to practice and intensity of practice compared to conventional therapy [1], [3], [8], [9]. In a systematic review, Brunner et al. [8] reported that serious gaming had a statistically significant impact for children to improve motor outcomes, but they emphasized that high quality randomized controlled trials are required in this area. Likewise, Taheri et al. [9] stressed that

3.3. Wearable sensing technologies for finger rehabilitation

Wearable gloves equipped with flex sensors are commonly used for motion tracking at the finger level as they provide reliable kinematic information, are inexpensive, and can be modified for use in the home [4], [7]. They are also able to assess functional categories of motion such as flexion/extension, abduction/adduction, pinching, grasping, releasing, and tapping, that correspond to activities of daily living [4], [7]. Flex-sensor gloves have a stronger reliability than camera-based systems in home use because of fewer occlusion issues.

3.4. Machine learning for gesture recognition

Machine learning is essential to transform sensor data into a functional and meaningful therapeutic feedback. Static gesture recognition has been demonstrated to have great success using SVMs and LSTM networks have also been demonstrated with effective results for sequences of dynamic patterns [6], [7]. In a review conducted by Huang et al. [7] on wearable-sensor and ML approaches for hand rehabilitation treatments, they noted that ML models improved both classification accuracy and therapy personalization; however, issues of calibration and long-term drift remain.

3.5. Motivation and engagement in pediatric rehabilitation

Gamification has been shown to be effective for increasing engagement in e-health applications [3], [8]. Sardi et al. [11] stated that gamified rehabilitation systems can improve adherence by utilization of gamified elements such as reward systems, adaptive challenges, or compelling narrative. Lewis et al. [10] underscored the critical component of parent involvement in rehabilitation, demonstrating children have longer engagement classes when parents tracked performance and encouraged practice. Movement-related emotional feedback through animations, sounds, and rewards fosters motivation, engagement, and motor learning [1], [8], [9].

3.6. Doctor, parent, and AI-assisted monitoring

Another important aspect of rehabilitation for childhood disabilities is parent monitoring and clinician support enabling long-term adherence. Lewis et al. [10] reported that caregivers emphasized the importance of progress dashboards and clinician feedback as they support their child. Unfortunately, real time clinician supervision is not likely in environments with scarce resources. AI-supported voice assistants can provide motivation prompts and adaptive support. Allen et al. [10] and Thiel et al. [11] described similar approaches with voice assistants to improve therapy continuity between clinician supported sessions.

3.7. Gaps and opportunities

While VR-based rehabilitation and the use of wearable sensors have been extensively researched, most systems are either too expensive or targeted for adult populations [7], [9], [11]. Few systems use wearer-able sensors, ML-based gesture recognition, virtual-reality (VR), and multi-layer monitoring (physician, parent, and AI) in a single system used for pediatric hemiplegia. The proposed Magic Quest: The Enchanted Fingers closes these gaps by integrating therapeutic exercises with a fantasy adventure game, while providing clinical oversight, parent engagement, and AI-based incentivization.

3.8. The Demand for Affordable, Integrated Pediatric Finger Rehabilitation in Sri Lanka.

Even though high-tech rehabilitation systems (i.e., robotic exoskeletons or camera-based motion capture) can produce specific feedback/movement assist, they are too expensive, fragile, and non-applicable beyond a temporary state in low-resource [7], [9] contexts like in Sri Lanka.Interestingly enough, while high-resource countries can budget for these systems, children in Sri Lanka cannot afford even basic rehabilitation, partly due to prohibitive prices, a shortage of therapists, and the inability for many children to travel to rehabilitation facilities [2], [3]. Clearly, there is a severe gap in access to clinically valid and functionally-inexpensive, portable, and culturally/contextually-relevant technologies for more children to access in order to facilitate pediatric rehabilitation in developing areas**.**

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

Research Focus	**Key Strengths**	**Key Limitations**	**Relevance to Our Project**
VR for Engagement	Improves motivation, adherence, and practice intensity; fosters neuroplasticity**.**	Often limited to generic hand controllers; lacks fine finger tracking; minimal therapeutic feedback.	Provides a framework for engagement. We extend it with finger-level kinematics mapped directly into therapeutic VR gameplay.
Wearable Gloves	Inexpensive, portable, tracks functional categories of finger motion; reliable in home use.	Often used for offline assessment only; limited integration with adaptive therapeutic systems.	lex-sensor gloves form the foundation of our data capture system, enabling real-time tracking of six core finger movement types.
Machine Learning	Enables automated classification, personalization, and gesture recognition with high accuracy.	Calibration issues and drift; rarely integrated with pediatric therapy platforms in real-time.	We combine SVM (for static gestures) and LSTM (for dynamic gestures) into a real-time feedback loop for rehabilitation.
Gamification & Motivation	Enhances adherence, emotional engagement, and practice time; parental involvement boosts outcomes.	Often superficial gamification; lacks narrative depth or adaptive difficulty.	Our “Magic Quest: Enchanted Fingers” employs narrative-driven gamification, adaptive challenges, and parent dashboards**.**
High-end Systems	High precision, full motion capture, effective for research.	Prohibitively expensive, non-portable, unsuitable for home use in Sri Lanka.	Underscores the need for affordable alternatives; our system delivers functionality at a fraction of the cost.
Our Integrated System	Low-cost, child-centered, combines flex sensors, ML, VR,	Yet to be clinically validated at scale.	Directly addresses gaps by providing a unified, accessible

	and multi-layer support (doctor, parent, AI).		solution for pediatric hemiplegia rehabilitation in Sri Lanka.

3.9. Conclusion

The literature clearly shows a distinction: VR-based systems drive motivation but lack a detailed biomechanical fidelity while sensor-based systems contain a richness of data, but usually exist in a domain that is offline or usually intended for adult rehabilitation. Very few platforms exist, that combine both elements to create a single platform for children which is low cost and user-friendly. In addition, the devices or platforms that do exist, don't usually provide multiple levels of monitoring (particularly from a clinician, parents and AI-based assistants), which are particularly important in places like Sri Lanka where access to therapy is limited.

This project will directly address these gaps through the implementation of Magic Quest: The Enchanted Fingers a unified technology that combines flex-sensor glove technology, ML gesture recognition, immersive VR-based gamification, and a multi-support ecosystem. The system merges clinical efficacy through a fantasy-inspired game with continuous supports from parent, doctors, and AI by adding levels of monitoring and ultimately addressing affordability and access. Ultimately, this research aims to provide a novel, culturally-appropriate, scalable rehabilitation intervention for hemiplegic children in Sri Lanka.

4. Research Gap

The current literature highlights many developments in VR rehabilitation, glove systems, and structured analysis of fine motion based on machine learning, all of which may benefit upper-limb motor rehabilitation. Wearable gloves and fine sensors together with Flex systems have potential to capture fine kinematic processes (e.g., grasping, pinching, finger tapping) with accurate precision [4], [5]. Machine-learning processes (SVM, LSTM) have individual characterized the rehabilitation gestures enabling adaptive to performance and personalized therapist training [6], [7]. The engagement in therapy including motivation, adherence, and, engagement are emphasized in children with the use of gamification with VR compared to traditional therapy [8].

On the other hand, there is an important gap in research using these new technologies into a feasible, economical, and child-based rehabilitation system in Sri Lanka, given the low-resource context. The VR rehabilitation of fine motor skills systems are generally conceived and developed in high-income countries relying on expensive glove exoskeletons, robotics devices, or commercial VR headsets that are impractical or inaccessible for widespread clinical or home use in Sri Lanka [9]. Furthermore, many of the fine motor systems have focused primarily on training of the upper limb at the shoulder and elbow instead of rehabilitation of the fingers that may primarily impact functional independence during daily activities (e.g., writing, food consumption, dressing) [5], [6].

Another gap is that most available sensor-based rehabilitation systems do not provide real-time corrective feedback. The available systems record kinematic data for analysis after therapy, but it is rare that they incorporate this data into real-time guidance to the child, within the VR gameplay. This current gap limits the potential for motor learning as real-time feedback can greatly enhance neuroplasticity.

In addition, most of the above studies have developed and subsequently validated their systems with adult stroke survivors as their target population [7] and have not focused specifically on the pediatric population. Children with hemiplegia have specific developmental, motivational, and engaging needs that will not be found with adult rehabilitation, so repurposing a platform designed for adults will not effectively meet these needs. In the Sri Lankan context, these realities are complicated further by systemic barriers which include a shortage of pediatric therapists, expensive therapy sessions, rehabilitation centers being scarce in the rural areas and non-adherence to home-based therapy due to boredom and a lack of supervision and motivation [2].

Thus, the research gap identified is the lack of a low-cost, integrated VR rehabilitation system for finger rehabilitation in children with hemiplegia in Sri Lanka. A system must combine wearable flex-sensor technology, gesture recognition by ML, immersive VR gaming and caregiver/clinician support to develop a child-centered integrated platform that provides therapy and maintains motivation/access outside of highly specialized clinical environments.

5. Research Problem

The above literature survey poses the following research question:

What game-based rehabilitation framework can be developed that integrates doctor monitoring, parental supervision, and AI-driven voice assistance to improve elbow and finger motor function in children with hemiplegia?

1. Present rehabilitation systems for children with hemiplegia on orthosis support only reinforce traditional physiotherapy and/or employ game-based rehabilitation as a generic concept, where patient-tailored personalization occurs very little.
2. Most rehabilitation games lack real time monitoring by experienced healthcare professionals, inhibiting a doctor's ability to switch the treatment plan based on their assessment of a child's success.
3. There is limited engagement of parents, even though they play a vital role in being the monitored practice provider and motivator of children.
4. Current rehabilitation systems do not leverage voice-assisted guided encouragement as augmented engagement with patients, especially when a doctor is not present.
5. Existing systems do not provide detailed monitoring of finger level motion required to positively affect fine motor control in hemiplegic children.

6. Research Question

The aforementioned literature review ultimately leads to the following research question:

What game-based rehabilitation framework could be constructed that incorporates doctor monitoring, parental oversight, and AI powered voice-based encouragement that will contribute to the improvement of elbow and finger function in children with hemiplegia? In answering this question we propose the construction of the intelligent rehabilitation game based system that performs the following tasks:To answer this question, we propose the development of an intelligent rehabilitation game-based system with the following functionalities:

- Doctor monitoring and advisory support – Doctors can remotely monitor progress using the system and advise.
- Parental monitoring – Parents will be able to monitor progress and ensure their children are maintaining a robust training cadence through motivation.
- Voice assistant encouragement – The AI will provide realtime encouragement and motivation when a doctor cannot.

- Game-based therapy with fine motor tracking – The system will track elbow joint motion and track movement at the finger joint level with the ability to integrate movement into engaging magical/adventure-style gameplay.
- Progress reporting – Will generate reports that provide all performance information for both parents and doctors to assist in directing therapy.

7. Objectives

7.1. Main Objective

The main objective of this research is to design, develop, and validate a low-cost, gamified finger rehabilitation system that integrates wearable flex-sensor gloves, machine learning models, and virtual reality to provide real-time feedback and enhance fine motor recovery in children with hemiplegia.

7.2. Specific Objectives

7.2.1. To design and implement a wearable glove-based hardware and software pipeline for capturing and processing fine finger kinematics.

- Details: This involves embedding flex sensors into a glove to measure finger joint movements such as flexion/extension, abduction/adduction, pinching, grasping, releasing, and tapping. A microcontroller (ESP32) will be programmed to read sensor outputs, process signals (normalization and calibration), and transmit them via Bluetooth/WebSocket to a PC or VR platform in real-time.

7.2.2. To develop and optimize machine learning models for accurate classification of finger movements and gesture recognition.

- Details: This includes collecting labeled datasets of finger motions from both healthy and hemiplegic children. Static gestures will be classified using Support Vector Machines (SVM), while dynamic sequential patterns (e.g., tapping) will be recognized using Long Short-Term Memory (LSTM) networks. The models will be trained to achieve a minimum accuracy of 90%, ensuring reliability for therapeutic use.

7.2.3. To engineer an immersive VR-based game environment that embeds therapeutic finger exercises into engaging gameplay

- Details: A Unity-based VR game, *Magic Quest: The Enchanted Fingers*, will be developed. Each finger movement will correspond to magical in-game actions (e.g., pinching → lighting crystals, grasping → opening treasure chests). The design will be guided by occupational therapists to ensure the game mechanics align with therapeutic goals while maintaining a narrative-driven, child-friendly experience.

7.2.4. To integrate a multi-modal real-time feedback system that guides and motivates correct finger movements during gameplay

- **Details: Outputs from the ML models will drive feedback mechanisms:**
    - Visual: Highlighting correct/incorrect finger movements on the VR avatar, glowing effects for successful gestures.
    - Auditory: Reward sounds, magical tones, or subtle corrections to guide children without discouragement.
    - Gamified: Linking scores, rewards, and magical achievements directly to the quality and accuracy of finger movements, not only task completion.

7.2.5. To evaluate the system's technical performance, usability, and engagement through pilot testing with hemiplegic children in Sri Lanka.

- **Details: A user study will be conducted to assess:**
    - Technical Performance: Sensor accuracy, ML classification accuracy, system latency, and real-time responsiveness.
    - Usability: Using standardized measures such as the System Usability Scale (SUS) and qualitative feedback from children, parents, and therapists.
    - Engagement: Observed through game playtime, adherence rates, and motivational response.

8. Methodology

The proposed system follows a structured approach to guarantee technical integrity, clinical relevance, and influence readiness for low-resource settings, such as Sri Lanka. The creation process is divided into seven phases: hardware design, data collection, machine learning model, VR game, real-time feedback, monitoring of doctors and parents, and evaluation. Each phase is reviewed in detail to provide support for providing rehabilitation for hemiplegic children, by gamified VR therapy.

8.1. Component Overview

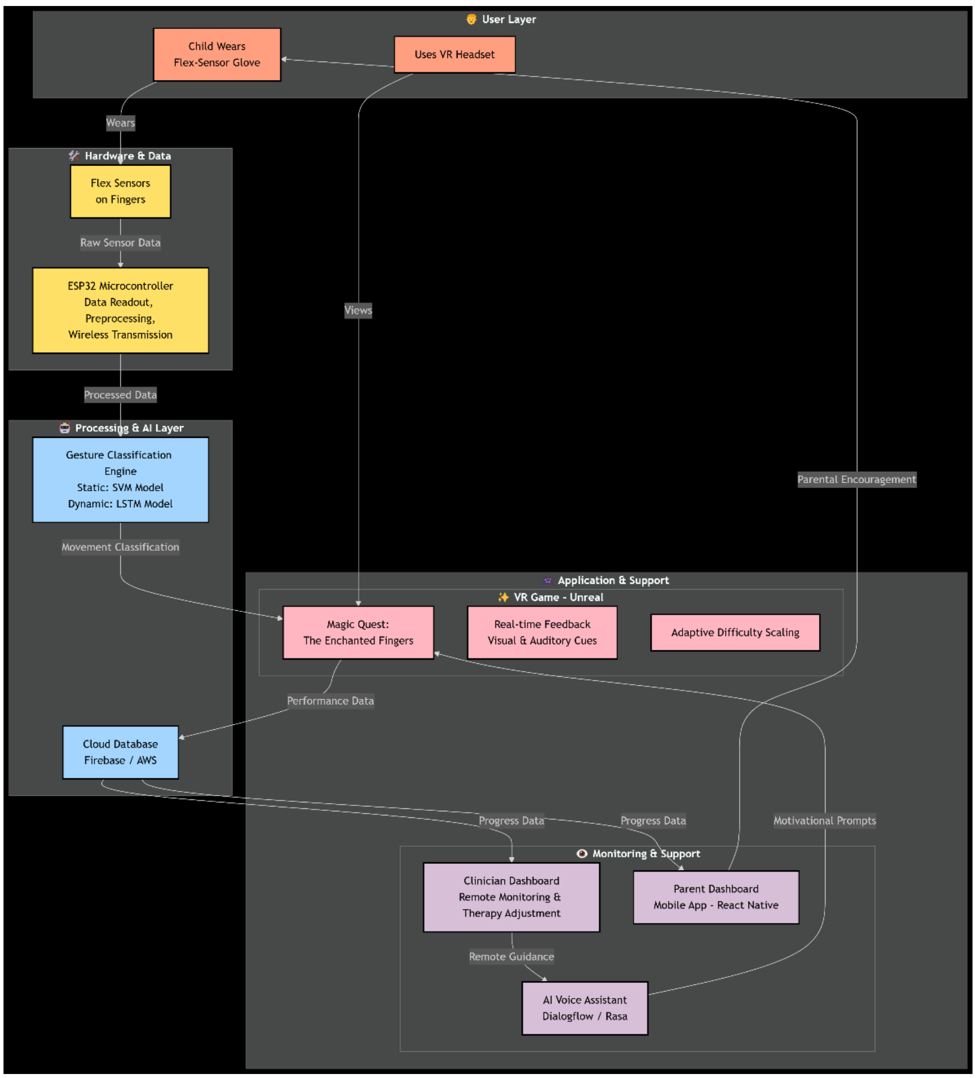

Figure 1:System Overview

8.2. Sensor Selection and Hardware Design

The system is built around wearable rehabilitation glove to be able to capture fine finger movements. Five flex sensors are embedded into a child-friendly glove made from fabric, one for each finger. The flex sensor is attached to the glove so that the sensor measures the angular displacement of each finger bending. The flex sensor was chosen because they are: inexpensive, light-weight, sensitive, and it has been shown to successfully integrate into upper limb rehabilitation systems [7], which is ideal in the pediatric context. The sensors attached to the glove create a secure basis while keeping the wearer comfortable, with soft padding and adjustable straps designed to fit all children's hands, supporting difference in use between different children.

For collecting data, the ESP32 microcontroller was selected for its low-cost, compact form factor, and built-in Wi-Fi and Bluetooth connectivity, which makes communication with virtual reality (VR) platforms seamless. Sensor calibration involves a two-step process; static calibration that sets the zero and maximum bending locations, then dynamic calibration that logs bend positions for limb angles within personalized motion baselines. The glove does not use a battery solution as this adds costs and risks, instead is powered through the ESP32 board, which alone is plugged into a breadboard power supply. Male-female jumper wires connected the components providing stability during prototyping and clinical evaluations. Again, this setup can be run continuously and safely at home or clinical environments without relying on rechargeable batteries.

8.3. Data Collection and Preprocessing

Data collection begins with the creation of a benchmark dataset. First, healthy children will provide standardized hand movements with the goal of establishing normative ranges for finger flexion, finger extension, pinching, tapping, abduction and adduction. In order to direct rehabilitation, we will also obtain data from the unaffected hand of hemiplegic children, which will then allow our system to create exercises based on the functional abilities of each child. More importantly, if you are simply taking unordered data and trying to normalize it, without utilizing the data from the unaffected hand the challenge will be to objectively base her rehabilitation on normative averages.

Raw signals provided by the sensors are often noisy. As such, the data must be filtered. The Kalman filter will smooth the angular trajectories of the continuous movements, and the moving average (MA) filter will remove jitter caused by fluctuations in the sensors. After the noise is discarded, the signals will be segmented into discrete windows relating to each of the movements and the samples will be categorized into one of the six target categories. The features we pull out include bending angles, velocity, acceleration, as well as the temporal sequence elements associated with hand movements, such as tapping frequency and hold duration. The collection of feature data enables a more thorough dataset for training and movement recognition and classification machine learning [8].

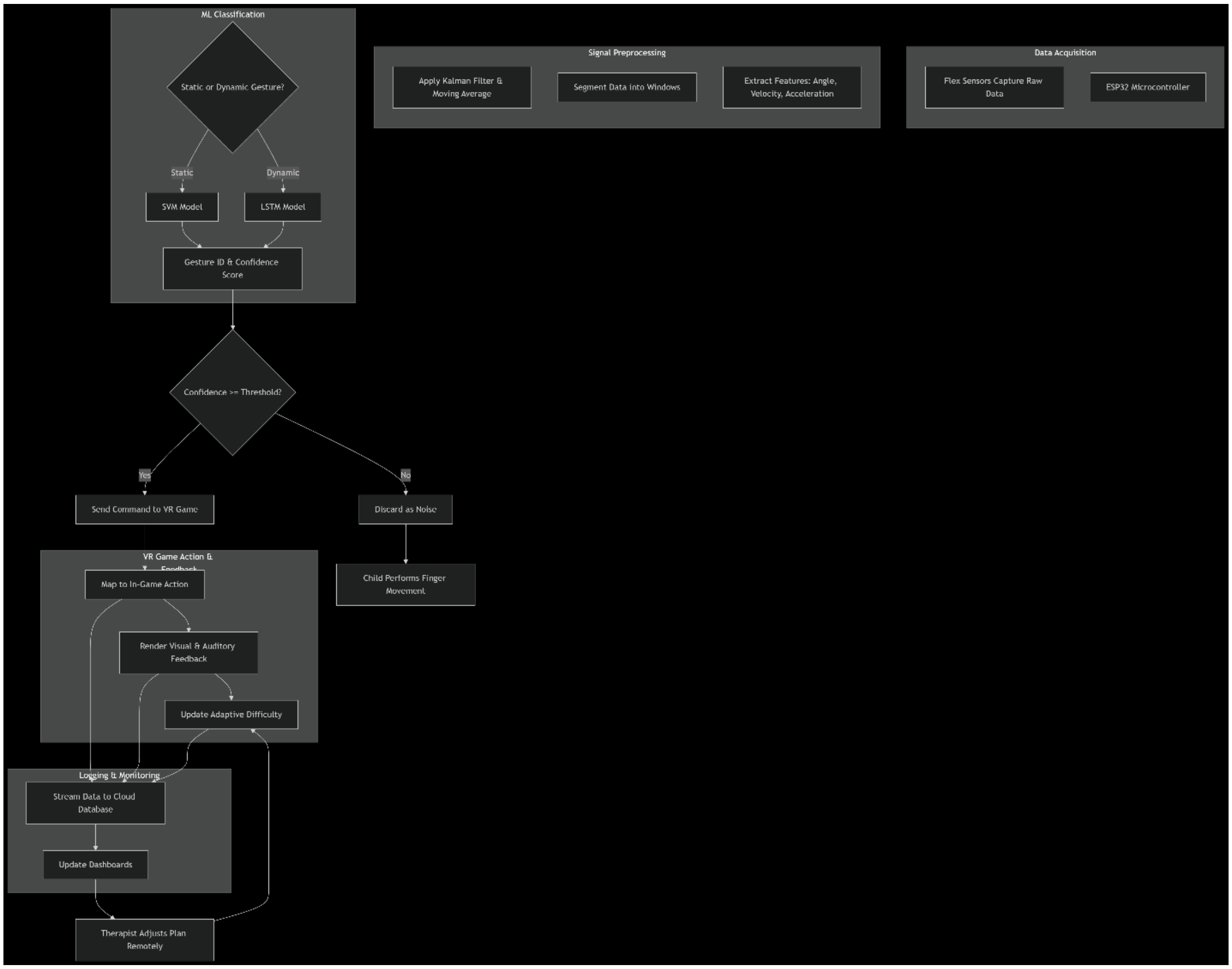

Figure 2:Data Processing

8.4. Machine Learning Model Development

The system employs both static and dynamic gesture recognition models. For static gestures, such as holding a pinch or grasp, Support Vector Machines (SVM) are used due to their robustness with small datasets and high classification accuracy [7]. For dynamic gestures, such as sequential tapping, Long Short-Term Memory (LSTM) networks are applied to capture temporal dependencies in movement sequences [4].

The dataset is divided into training (70%), validation (15%), and testing (15%) subsets, with k-fold cross-validation used to minimize overfitting. Model evaluation metrics include accuracy, precision, recall, F1-score, and confusion matrices to identify misclassified gestures. To ensure real-time deployment, trained models are optimized into lightweight formats using TensorFlow Lite or ONNX, which are embedded into the ESP32 and VR platforms. This allows low-latency gesture recognition within the game environment while maintaining computational efficiency [7].

8.5. VR Game Design and Integration

To enhance engagement, the rehabilitation exercises are embedded within a gamified VR environment called *Magic Quest: The Enchanted Fingers*. This narrative-driven game places children in a magical world where finger movements correspond to spell-casting, unlocking runes, and activating enchanted objects. Each movement category maps to a distinct in-game action—for example, flexion/extension casts spells, pinching activates crystals, grasping opens treasure chests, tapping unlocks magical runes, and abduction/adduction directs energy beams.

Adaptive difficulty scaling ensures the game adjusts to the child's progress. If consistent improvement is detected, challenges such as faster tapping or longer holds are introduced. Conversely, if frustration or fatigue is detected, the system lowers difficulty to maintain motivation. The game is developed using Unreal Engine, which is compatible with affordable VR headsets, thereby ensuring accessibility in low-resource contexts [1][4][9].

8.6. Real-Time Feedback and Emotion Adaptation

Immediate and engaging feedback is critical for sustained participation. The system provides visual rewards such as glowing spells, fireworks, or magical creatures that appear upon successful gestures, alongside auditory feedback in the form of playful music and encouraging sound effects. To maintain motivation, emotion-adaptive gameplay adjusts difficulty based on performance metrics such as failed attempts, idle time, or slowed responses [2][3].

Additionally, an AI-driven narrator offers motivational guidance (e.g., "Great job, wizard!") to keep children encouraged even in the absence of direct human supervision. This approach combines intrinsic game rewards with extrinsic motivational cues, reinforcing consistent participation and improving therapy adherence [9][10].

8.7. Doctor and Parent Monitoring

A core innovation of this system is its dual monitoring mechanism. Data from the glove is transmitted to a secure cloud-based dashboard accessible to clinicians. Doctors can remotely track progress, analyze gesture quality, and update rehabilitation plans. In addition, tele-consultation features allow for real-time video sessions where doctors can directly observe and guide exercises [6][10].

In cases where a doctor is unavailable, an integrated AI voice assistant ensures continuity of therapy. The assistant delivers instructions, encouragement, and playful narration to sustain engagement and adherence. Parents also play a key role in monitoring progress through a mobile caregiver dashboard, which displays daily exercise completion, accuracy, game scores, and adherence rates. This involvement allows parents to encourage consistent practice and strengthens the home-clinic rehabilitation link [10][11].

8.8. Evaluation and Deployment

The system undergoes pilot testing in collaboration with pediatric rehabilitation centers. Both healthy and hemiplegic children participate in trials to validate usability, engagement, and clinical effectiveness. Clinical evaluation metrics include improvements in range of motion, grip strength, and fine motor skills, assessed using standardized tools such as the Melbourne Assessment of Unilateral Upper Limb Function [1]. Usability is measured using the System Usability Scale (SUS) and caregiver feedback, while engagement is tracked through game metrics such as session duration, frequency of play, and progression in difficulty levels [3][8].

For deployment, the system is optimized for low-cost hardware components such as ESP32, flex sensors, and affordable VR headsets. This ensures accessibility not only in clinical environments but also for home-based rehabilitation in Sri Lanka and similar contexts where cost and availability are critical considerations [5][9].

8.9. Technology Stack

The successful implementation of the proposed rehabilitation gaming system relies on a carefully designed technology stack that integrates hardware, firmware, data handling, machine learning, game development, cloud services, mobile interfaces, and AI-driven support. Each layer works cohesively to provide a seamless experience for patients, doctors, and caregivers while ensuring low cost, scalability, and clinical relevance.

8.9.1 Hardware Layer:

The hardware foundation of the system is built upon the **ESP32 microcontroller**, which provides an affordable and compact solution with integrated Wi-Fi and Bluetooth connectivity. Its processing capabilities make it ideal for real-time biomedical applications in low-resource environments [7]. The ESP32 interfaces with **flex sensors** attached to the rehabilitation glove, capturing finger joint angular displacement to assess motor function, as demonstrated in previous rehabilitation studies [7]. A **breadboard power distribution setup** is used instead of rechargeable Li-ion batteries, ensuring safer prototyping and reducing risks in pediatric use. Male-female jumper wires provide stable and flexible component connectivity during testing phases. For immersion, the glove is connected to low-cost VR headsets such as **Oculus Quest**, which have shown clinical promise in upper-limb rehabilitation age up from 12 [4], [9].

8.9.2. Firmware and Data Handling Layer:

The ESP32 firmware is developed using the **Arduino IDE** and **MicroPython**, both lightweight platforms suitable for IoT and biomedical prototyping [7]. These environments enable efficient control of flex sensors and preprocessing of hand-movement data. Sensor signals are transmitted via **serial communication or Wi-Fi protocols**, ensuring low-latency transfer to the VR environment. Noise in raw signals is reduced through real-time filtering techniques, which are essential for maintaining gesture accuracy in rehabilitation [7].

8.9.3. Machine Learning Layer:

Machine learning plays a critical role in personalizing rehabilitation. **Support Vector Machines (SVM)** are used for static gesture recognition, while **Long Short-Term Memory (LSTM) networks** handle sequential and dynamic gestures such as tapping or grasping [3], [7]. Models are trained in **Python** using TensorFlow Lite and ONNX for lightweight deployment, ensuring real-time performance even on embedded systems. Preprocessing techniques such as **Kalman filtering** and **moving average smoothing** improve signal stability and enhance classification accuracy [7]. By embedding trained models into the ESP32 and VR game, the system ensures robust gesture recognition during therapy sessions.

8.9.4. Game Development Layer:

To improve engagement and motivation, rehabilitation exercises are embedded into an interactive VR game environment built on **Unreal Engine**. Prior studies confirm that VR-based games significantly enhance adherence, motivation, and motor outcomes in children with hemiplegia [1], [3], [4]. Gesture recognition APIs are integrated into the game engine to translate real-world hand movements into meaningful in-game actions. Adaptive difficulty scaling ensures the gameplay dynamically adjusts to patient performance, maintaining therapeutic challenge without overwhelming the child [9], [10].

8.9.5. Cloud and Monitoring Layer:

Cloud infrastructure is crucial for enabling doctor and caregiver monitoring. Services such as **Firebase** or **AWS** are used to securely store session data and stream progress to clinician dashboards [6], [10]. Doctors can remotely analyze exercise performance, track rehabilitation progress, and adjust therapy protocols in real time. This remote accessibility addresses critical barriers in pediatric rehabilitation, particularly in low-resource environments such as Sri Lanka [2], [9].

8.9.6. Mobile and Caregiver Interface Layer:

Recognizing the role of caregivers in pediatric rehabilitation, the system includes a **mobile monitoring application** developed using cross-platform frameworks such as **React Native**. The app enables parents to review daily reports, therapy progress, and motivational feedback, strengthening the home-clinic rehabilitation link [10], [11]. Notifications encourage consistent participation, while summary analytics allow caregivers to support and motivate their child in daily therapy routines.

8.9.7. AI-driven Support Layer:

A novel feature of the system is its **AI voice assistant**, implemented using platforms like **Dialogflow** or **Rasa**, which ensures continuity of therapy even when doctors are unavailable. The assistant provides real-time motivational feedback, guides children through exercises, and encourages adherence with playful narration. Studies confirm that such AI-driven interventions improve engagement and reduce dropout rates in home-based rehabilitation programs [2], [9], [10]. When doctors are available, the system supports direct supervision through tele-consultation features, ensuring a hybrid human-AI monitoring model.

Overall, this **multi-layered technology stack** ensures low latency, scalability, and adaptability. Its modular design allows integration of future innovations such as haptic feedback, advanced AI personalization, and expanded VR rehabilitation scenarios, aligning with global trends in gamified therapy for motor impairments [3], [7], [8].

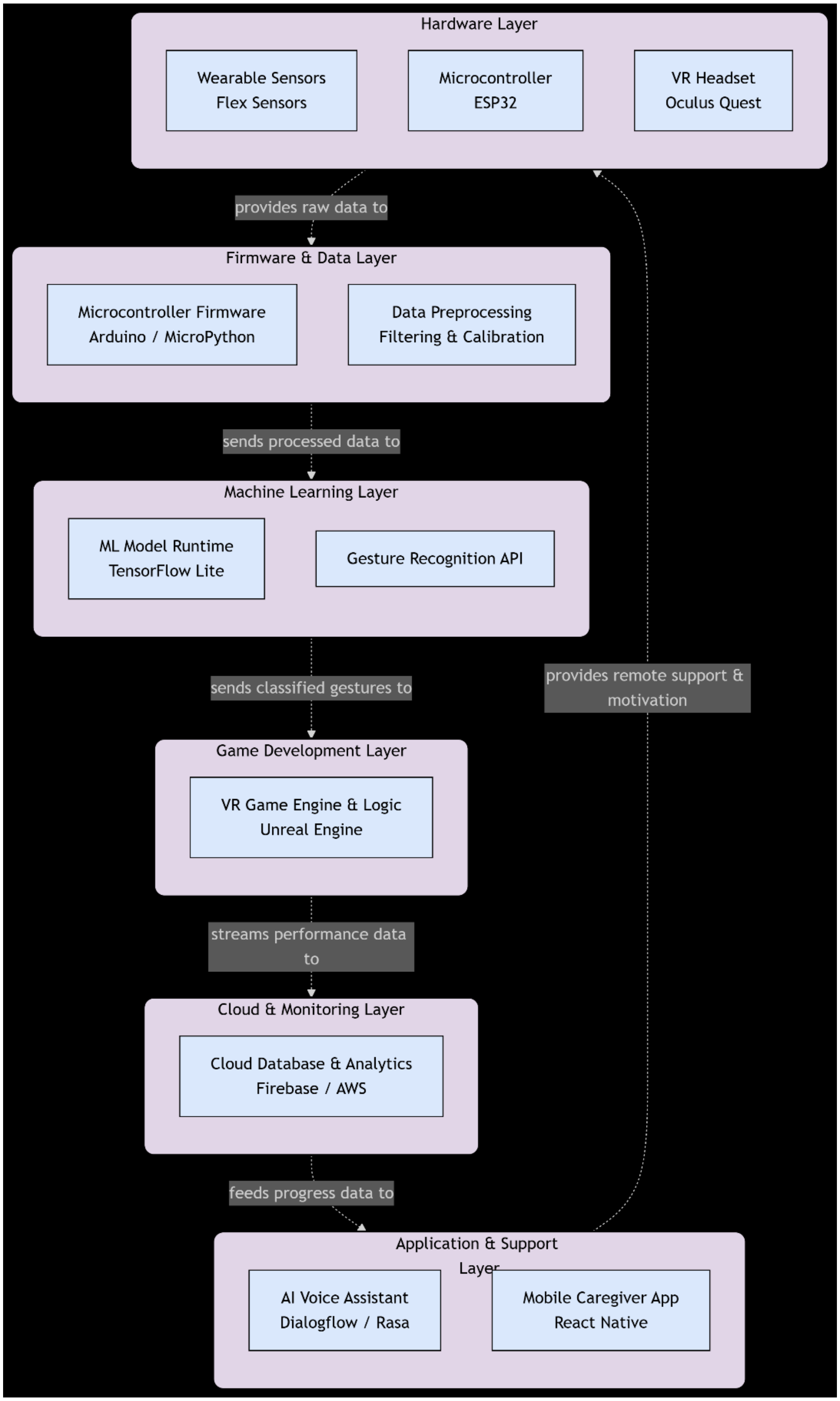

Figure 3:Relationship between Layers

9. Functional and Non-Functional Requirements

9.1. Functional Requirements

The system is designed with several key functional requirements to ensure usability, effectiveness, and clinical applicability:

9.1.1. Real-Time Finger Motion Tracking:

The system must be capable of capturing and processing finger joint movements in real time using flex sensors connected through an ESP32 microcontroller. This includes tracking flexion and extension angles of individual fingers to provide accurate motion profiles. Wearable sensor-based rehabilitation has been widely adopted due to its affordability, portability, and accuracy in capturing upper-limb kinematics [7].

9.1.2. Gesture Recognition and Rehabilitation Exercises:

The system must recognize predefined rehabilitation gestures from sensor data and map them to corresponding VR-based game interactions. This ensures that patients perform therapeutic exercises correctly while remaining engaged. Gesture-based VR rehabilitation has been shown to improve motivation and adherence to therapy in children [1], [4], [6].

9.1.3. Virtual Reality (VR) Game-Based Rehabilitation:

The system must provide immersive VR game environments that encourage repetitive, task-oriented finger movements. VR has been demonstrated to enhance motor learning, neuroplasticity, and patient engagement, making it an effective tool for pediatric rehabilitation [3], [9], [10].

9.1.4. Remote Monitoring and Clinician Dashboard:

The system must include a secure cloud-based dashboard to enable clinicians to remotely track patient progress, analyze performance metrics, and adjust therapy plans as needed. Tele-rehabilitation features are critical for continuous care and accessibility, particularly for children with mobility challenges [2], [6], [8].

9.1.5. Caregiver and Patient Support Interface:

A mobile application must be provided for caregivers, offering features such as session reminders, progress visualization, and motivational feedback. Active caregiver involvement has been shown to significantly improve pediatric rehabilitation adherence and outcomes [5], [10].

9.2. Non-Functional Requirements

9.2.1. Accuracy of Motion Tracking:

The machine learning and signal processing models must achieve at least 85% accuracy in detecting and classifying finger rehabilitation movements. Previous studies indicate that accuracy thresholds above 80% are required for reliable outcomes in clinical motion-tracking systems [7]. Thus, achieving ≥85% accuracy is necessary for clinical adoption.

9.2.2. System Reliability and Low Latency:

The system must ensure low-latency data transmission between the flex sensors, ESP32 microcontroller, and VR environment. Delays greater than 100 ms can reduce immersion and negatively impact rehabilitation effectiveness [4].

9.2.3. Scalability and Cost-Effectiveness:

The system must be modular and scalable, enabling integration with additional sensors, new VR environments, or advanced AI modules without significant hardware replacement. Using affordable hardware such as ESP32 microcontrollers and low-cost VR headsets makes the system accessible for pediatric care [5], [8].

9.2.4. Usability and Engagement:

The system must provide a child-friendly, intuitive, and motivational experience. Rehabilitation outcomes strongly depend on engagement and willingness to perform repetitive tasks, particularly in children [3], [9], [11].

9.2.5. Data Security and Privacy:

Patient and caregiver data must be transmitted and stored securely using encryption techniques. As this system deals with sensitive pediatric health data, it must comply with data protection regulations (such as HIPAA or GDPR), ensuring clinician and caregiver confidence in its use [2], [6].

9.3. User Requirements

9.3.1. For Children (Patients)

- Engaging and Motivating Experience:
  The system must provide immersive and playful VR games that make rehabilitation enjoyable and encourage regular practice.
- Intuitive Controls:
  Finger movements should naturally translate to in-game actions without requiring complex instructions.
- Immediate Feedback:
  The system should provide real-time visual and auditory feedback to indicate correct or incorrect finger movements.
- Adaptive Difficulty:
  Game challenges must adjust automatically based on the child's progress, ensuring therapy remains appropriately challenging but not frustrating.
- Safe and Comfortable Use:
  Gloves, sensors, and VR equipment must be ergonomically designed for small hands and safe for prolonged use.

9.3.2. For Caregivers/Parents

- **Progress Monitoring:**
  The system should provide clear and easy-to-understand progress reports showing the child's improvement over time.
- **Session Management:**
  Caregivers should receive reminders for therapy sessions and be able to track adherence.
- **Guidance and Support:**
  The system should offer instructions or notifications when the child is performing exercises incorrectly, allowing parents to provide support.
- **Remote Assistance:**
  Caregivers should be able to consult with clinicians through the system's dashboard when needed.

9.3.3. For Clinicians/Therapists

- **Remote Monitoring and Analysis:**

Clinicians should have access to detailed patient data, including finger movement metrics, exercise completion, and compensation patterns.

- **Customizable Therapy Plans:**

The system must allow therapists to adjust exercises, difficulty levels, and repetitions according to the child's needs.

- **Integration of ML Insights:**

Real-time ML analysis of movement quality should help clinicians identify compensatory strategies and modify therapy plans accordingly.

- **Data Security and Compliance:**

Patient data must be securely stored and comply with healthcare privacy standards to allow safe remote supervision.

10. PROJECT COMMENCEMENT

10.1. WORK BREAKDOWN STRUCTURE

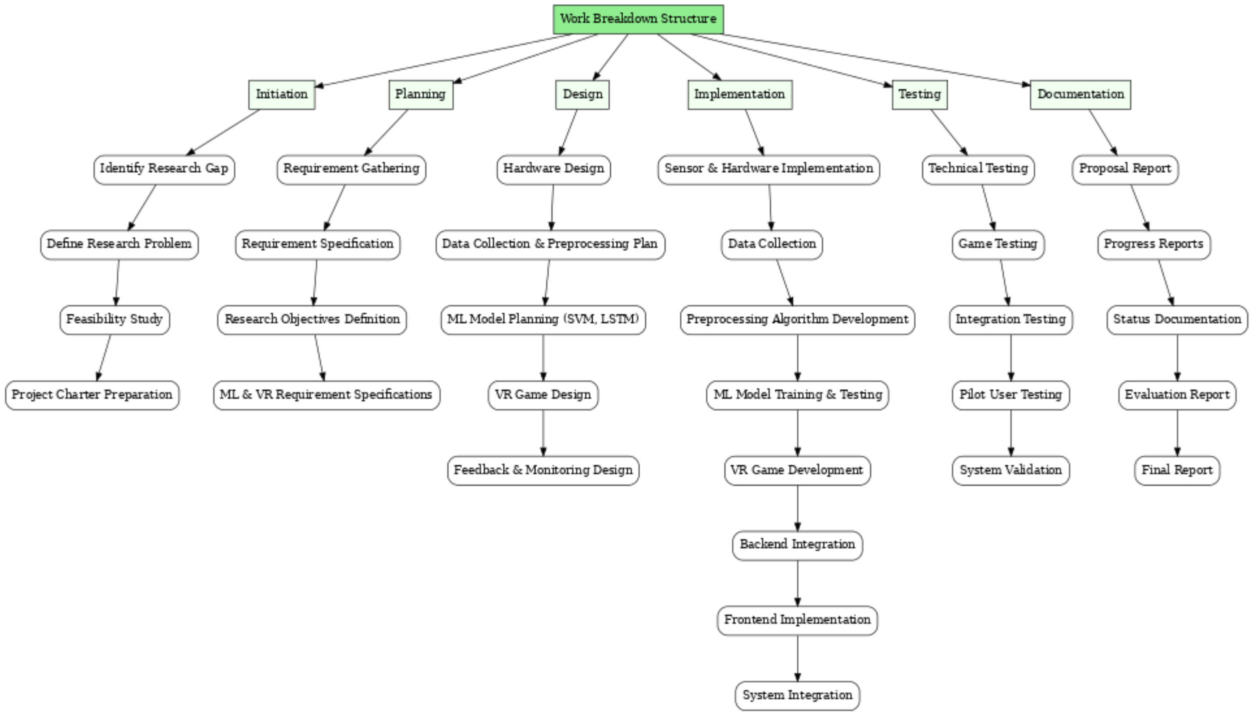

Figure 4:Work Breakdown Structure

10.2. Gantt Chart

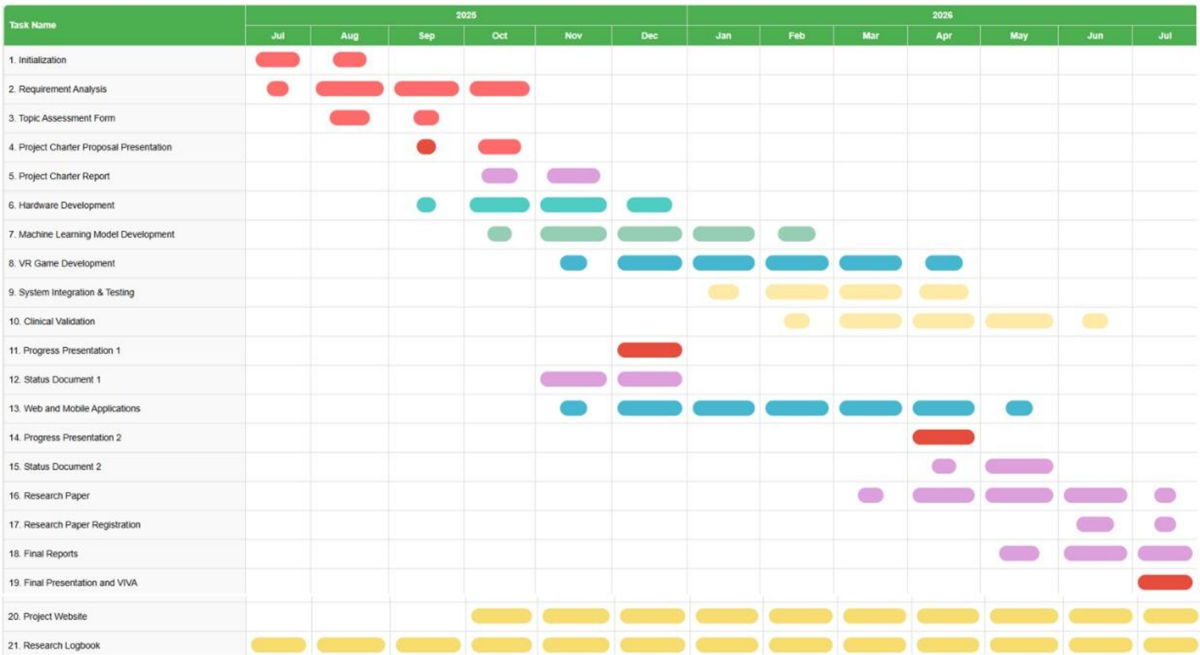

Figure 5: Gantt Chart

11. DESCRIPTIONS OF PERSONAL AND FACILITIES

11.1. Facilitators

- Mr. Didula Thanaweera Arachchi - Sri Lanka Institute of Information Technology
- Mr. Eishan Dinuka - Sri Lanka Institute of Information Technology
- Mr. Buddika Senavirathne – Head of Physiotherapy in Sirimavo Bandaranaike Specialized Children's Hospital, Kandy, Sri Lanka.

11.2. Facilities

- Sirimavo Bandaranaike Specialized Children's Hospital, Kandy, Sri Lanka.

12. Commercialization

The primary target users of this system are pediatric rehabilitation centers, clinics, and hospitals that provide therapy for children with hemiplegia or other upper-limb motor impairments. The system offers an affordable, portable, and engaging rehabilitation solution, making it suitable for both clinical and home-based use.

11.1. Additional potential markets and user groups

- Home-based caregivers and parents: Families seeking convenient, safe, and motivating rehabilitation options for children at home.
- Pediatric physiotherapists and occupational therapists: Professionals who require objective monitoring, progress tracking, and remote patient management tools.
- Educational institutions and therapy centers: Schools or centers offering therapeutic programs for children with motor disabilities.
- Research institutes and universities: Entities studying pediatric rehabilitation, human-computer interaction, or gamified therapy methods.
- Tele-rehabilitation service providers: Companies or startups offering remote therapy services, especially in regions with limited access to pediatric rehabilitation specialists.

The system's low-cost hardware components (ESP32 microcontroller, flex sensors, and VR headsets) and scalable software infrastructure allow for commercial viability in both high-resource and low-resource settings. Its modular architecture supports subscription-based software services, device sales, and integration with existing telehealth platforms, providing multiple revenue streams while improving accessibility to pediatric rehabilitation solutions.

12. HIGH-LEVEL DIAGRAM OF THE OVERALL SYSTEM

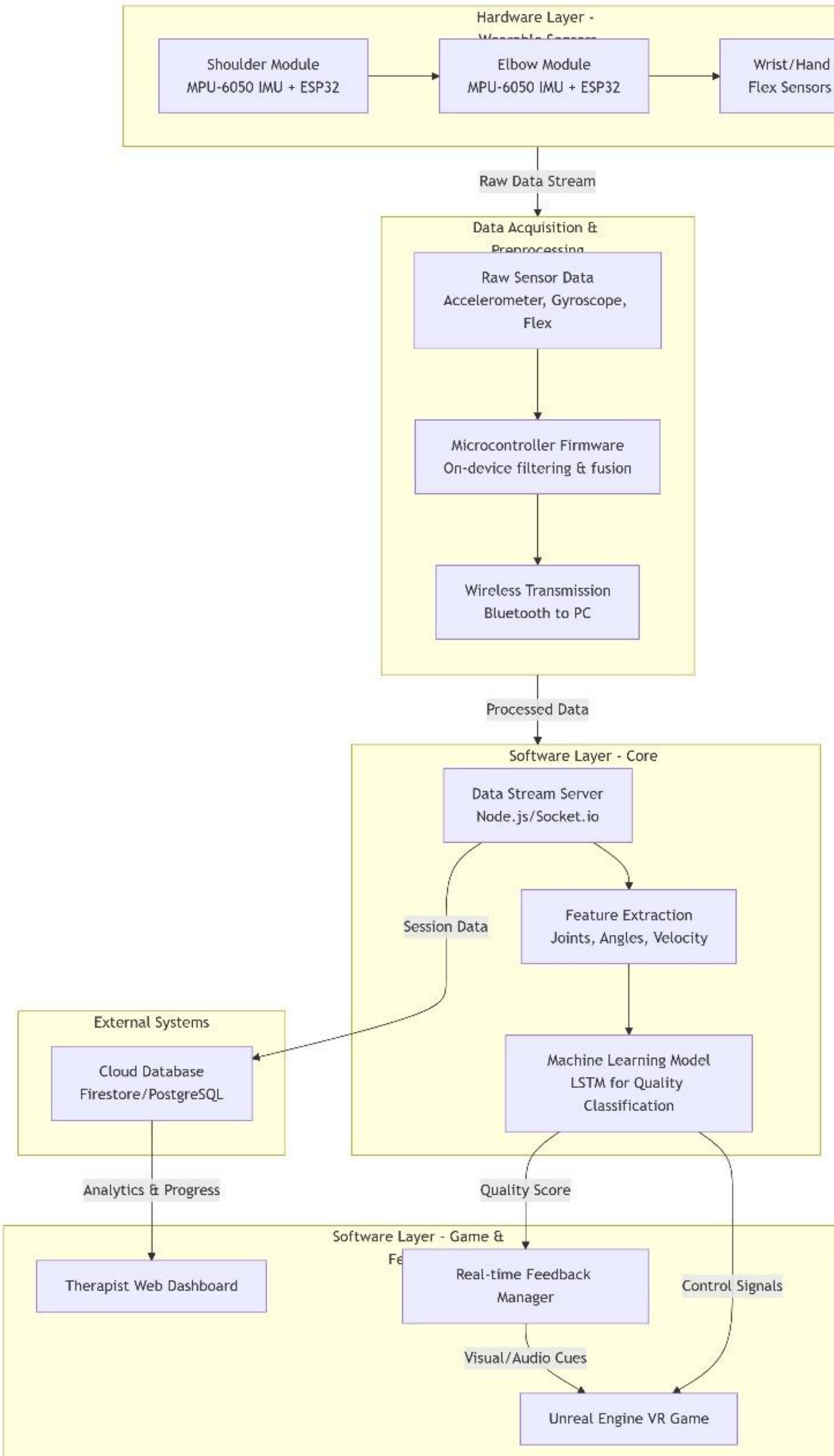

Figure 6:highlevel diagram of the overall System

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14. Appendix