



# **ArmiGo: Gamified VR-Based Therapy System for Upper Limb Rehabilitation in Children with Hemiplegia.**

Project Id: 25-26j472

## **Draft Project Proposal Report**

Weerasinghe D.N.T(IT22119230)

Supervisor- Mr. Didula Thanaweera Arachchi

Co-Supervisor- Mr. Eishan Weerasinghe

BSc. Special (Hons) in Information Technology, specialization in Software Engineering


Department of Computer Science and Software Engineering


Sri Lanka Institute of Information Technology

August 2025


## DECLARATION

We declare that this is our own work. 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.

Name	Student ID	Signature
Weerasinghe D.N.T	IT22119230	

  
.....  
MR Didula Thanaweera Arachchi  
(Supervisor)

28/08/2022  
.....  
Date

  
.....  
MR Eishan Dinuka  
(Co - Supervisor)

28/08/2022  
.....  
Date

## ABSTRACT

Hemiplegia in children, often resulting from perinatal stroke or cerebral palsy, typically affects better limb function. The hemodynamic dysfunction may considerably limit everyday activities such as eating, getting dressed, lifting items, and reaching. Traditional physiotherapy can improve the outcome but suffers from limited therapists, high costs, and accessibility challenges in low-resource settings. Additionally, repetitive exercises often reduce both motivation and adherence for children. In this project, we proposed a low-cost, wearable elbow rehabilitation system that combines Inertial Measurement Unit (IMU) sensors with machine learning (ML) and gamification by contextualizing the rehabilitation in virtual reality (VR).

Rehabilitation with a series of motions, either prescribed as a therapeutic exercise or attained functionally, was captured with an IMU that was mounted on an elastic elbow sleeve. Elbow movements included flexion, extension, pronation, supination, and reaching. In our system, ML algorithms take the series of motions performed by the users and classify and map them in real-time to the VR game, “Knight’s Quest: The Shield of Strength”, where the therapeutic motion selected mapped to an action in the VR game, such as raising a sword to defeat an enemy, striking an enemy's foreground obstacles, rotating the shield to block projectiles and collecting treasures. Input from multiple user profiles improves ML parameter learning and adaptations. By design, the game is immersed with adaptive difficulty, real-time visual, auditory feedback, and emotion-aware elements to enhance interest and motivation.

The proof of concept includes multiple levels of support that enable doctors to remotely monitor users, along with repeated therapy and input from their parents/caregivers. Caregivers would also have a report/dashboard. Pilot testing will provide initial feedback on the proposed design.

## List Of Contents

<b>DECLARATION</b> .....	2
<b>ABSTRACT</b> .....	1
<b>List of Figures</b> .....	4
1. Introduction.....	5
2. Background.....	7
3. Literature Review.....	9
<b>3.1.</b> Clinical context and rehabilitation requirements .....	9
<b>3.2.</b> Virtual reality (VR) and serious games as rehabilitation.....	9
<b>3.3.</b> In the field of elbow rehabilitation, wearable sensing technologies .....	9
<b>3.4.</b> Machine learning for movement classification.....	10
<b>3.5.</b> Motivation and Engagement in pediatric Rehabilitation .....	10
<b>3.6.</b> Doctor, parent, and AI-assisted monitoring.....	10
<b>3.7.</b> Conclusion .....	12
4. Research Gap .....	13
5. Research Problem .....	14
6. Research Question .....	15
7. Objectives .....	16
<b>7.1.</b> General Goal .....	16
<b>7.2.</b> Specified objectives .....	16
8. Outcomes .....	17
9. Methodology.....	18
<b>9.1. System Overview</b> .....	18
9.1.1. Component Overview .....	18
<b>9.2. Component Used</b> .....	19
9.2.1. Sensor selection and hardware design .....	19
9.2.2. Data Collection and Data Preprocessing.....	19
9.2.3. Machine Learning Model Development .....	19
9.2.4. Virtual Reality Game Design and Integration .....	20

9.2.5.	Feedback and Motivation Live .....	20
9.2.6.	Doctor and Parent Monitoring .....	21
9.2.7.	Evaluation and Deployment.....	21
<b>9.3.</b>	<b>Technologies .....</b>	<b>22</b>
9.3.1.	Hardware Layer .....	22
9.3.2.	Firmware and Data Handling Layer .....	22
9.3.3.	Machine Learning Layer.....	22
9.3.4.	Game Development Layer .....	24
9.3.5.	Cloud and Monitoring Layer .....	24
<b>10.</b>	<b>Functional and Non-Functional Requirements .....</b>	<b>25</b>
<b>10.1.</b>	<b>Functional Requirements .....</b>	<b>25</b>
10.1.1.	Real-Time Elbow Motion: .....	25
10.1.2.	Gesture Recognition and Rehabilitation Exercises:.....	25
10.1.3.	Virtual Reality (VR) Game-Based Rehabilitation: .....	25
10.1.4.	Remote Monitoring and Clinician Dashboard: .....	26
10.1.5.	Caregiver and Patient Support Interface: .....	26
<b>10.2.</b>	<b>Non-Functional Requirements .....</b>	<b>26</b>
10.2.1.	Accuracy of Motion Tracking:.....	26
10.2.2.	Reliability and low latency: .....	26
10.2.3.	Scalability and Cost: .....	26
10.2.4.	Usability and Engagement: .....	26
10.2.5.	Security and confidentiality of data: .....	27
<b>10.3.</b>	<b>User requirements .....</b>	<b>27</b>
10.3.1.	For Children (Patients).....	27
10.3.2.	For Caregivers/Parents.....	27
10.3.3.	For Clinicians/Therapists .....	28
<b>11.</b>	<b>Project Commencement .....</b>	<b>29</b>
<b>11.1.</b>	<b>Work Breakdown Structure .....</b>	<b>29</b>
<b>11.2.</b>	<b>Gantt Chart.....</b>	<b>29</b>

12.	Commercialization .....	30
13.	DESCRIPTIONS OF PERSONAL AND FACILITIES .....	31
13.1.	Facilitators.....	31
13.2.	Facilities.....	31
14.	High Level Diagram of the overall System .....	32
15.	Reference .....	33
16.	Appendix.....	34

## List of Tables

Table 1: Synthesis of Literature and Identification of the Research Gap .....	11
---	----

## List of Figures

Figure 1: Component Overview .....	18
Figure 2: Data Processing Diagram .....	23
Figure 3: Work Breakdown Structure .....	29
Figure 4 : Gantt chart .....	29
Figure 5:High Level diagram of the System .....	32

## 1. Introduction

Hemiplegia in pediatrics, typically a result of perinatal stroke or cerebral palsy, is defined by weakness or paralysis on one side of the body. Among the weaknesses present in the upper limbs, specifically, elbow joint strength and function are a particularly important impairment for reducing independence. The elbow is critical to facilitate fundamental daily activities, such as eating, dressing, grooming, reaching for objects, lifting, and carrying. When a child is unable to flex, extend, or pronate, and supinate, they struggle completing even the most basic self-care tasks. Reduced mobility inhibits physical independence but also negatively impacts the child psychologically, both in terms of their confidence as well as overall social participation [1], [2].

### Hemiplegia in Rehabilitation for Children with Elbow Weakness

Traditional rehabilitation techniques for hemiplegia to restore elbow motion typically consist of multiple sessions of repetitive physiotherapy, where the child receives instruction to engage in prescribed exercises with the intention of restoring motion and improving motor control. Traditional rehabilitative interventions are effective for motor recovery, but implementing these within low-resource settings such as Sri Lanka presents many challenges. Low resources, lack of pediatric rehabilitation specialists, high costs, and families having to arrive at therapy center locations, often traveling long distances, would negatively impact the accessibility to service continuity. The alternative way in which rehabilitation can occur, however, is often tedious and repetitive in nature, which directly affects patient adherence, particularly for children who typically lose motivation when engagement and playfulness are absent from the exercise or therapy experience [3],[4].

Over the past few years, technology has proven to be highly capable of addressing these restrictions. In particular, Inertial Measurement Units (IMUs), like the MPU6050, are an affordable and precise way to measure body movements by measuring acceleration and angular movement in real-time [5], [6]. When placed strategically on pediatric patients' arms, IMUs can accurately measure movements, including flexion, extension, pronation, supination, and reaching, and can also track incremental completion of rehabilitation periods concerned with motion quality. A machine learning (ML) approach to imu collected signals can classify movements into different categories, and ensure personalized and adaptive therapy programs, based on unique child's abilities [7], [8].

While sensor-based tracking improves accuracy, maintaining child engagement remains a crucial challenge. This is where Virtual Reality (VR) and gamification bring transformative value. Studies show that children are significantly more motivated when therapy is delivered in the form of interactive games rather than repetitive exercises [9], [10]. VR offers an immersive and playful environment where therapy becomes part of an adventure instead of a clinical task. In this project, the proposed system integrates IMU-based sensing and ML-driven movement classification into a VR game called “**Knight’s Quest: The Shield of Strength**”. In this game, children assume the role of a young knight tasked with restoring peace to a medieval kingdom. Each therapeutic elbow movement corresponds to a meaningful in-game action:

- Flexing the elbow raises the knight's sword.
- Extending the elbow will attack enemies or push away obstacles.
- Moving into pronation and supination will control and aim a magic shield.
- Reaching and lifting movements are used for collecting treasures, activating levers, or retrieving magic artifacts.

Through these combinations of activities, therapy is now a story-driven quest. Adaptive difficulty allows the game to gradually make it harder as the child improves, which avoids over-challenge or boredom. The real-time visual and auditory feedback reinforces the successful movements, such as the glowing effects when the shield successfully blocked an attack and sound effects when treasures were collected, which encourages motivation [11], [12].

In addition to captivating game design, the system also highlights a multi-level support ecosystem. Performance and progress data recorded during gameplay can be uploaded into a secure cloud-based platform, making the child’s therapy remotely accessible by doctors, who can track performance, identify trends, and adjust therapy protocols. The parents are given access to a caregiver dashboard which displays basic metrics such as participation and movement improvement, and in-game achievements, keeping parents engaged and involved in their child’s therapy. The system also includes an AI-driven voice assistant built in the VR environment which provides motivational suggestions, playful cues, and encouragement when doctors are not available, and regardless of the fact that support in these settings can be critical [13], [14].

This approach to hemiplegic elbow rehabilitation is able to address the three main problems: lack of access, lack of motivation, and lack of continued monitoring. By combining low-cost wearable IMU sensors, movement recognition using machine learning, and gamified VR therapy, this sustainable and engaging platform for rehabilitation can be developed. It has the potential to fill the healthcare gaps in Sri Lanka, and provide clinic-based and home-based therapy that is accessible, affordable, and effective for children with hemiplegia.

## 2. Background

For collecting data, the **ESP32 microcontroller** was chosen due to its affordability, compact size, and built-in Wi-Fi and Bluetooth connectivity, which allow seamless communication with the virtual reality (VR) platform. The elbow rehabilitation system uses **Inertial Measurement Units (IMUs)** and flex sensors to track forearm and elbow joint motions, including **flexion, extension, pronation, and supination**. Sensor calibration follows a two-step process: static calibration, which establishes baseline zero and maximum angles, and dynamic calibration, which records personalized ranges of motion for each patient. Similar to finger-tracking gloves, this system avoids complex battery packs for safety and cost reasons; instead, the ESP32 is powered through a stable breadboard power supply with jumper-wired connections, enabling continuous and safe use in clinical or home environments.

Elbow function is crucial for performing **Activities of Daily Living (ADLs)** such as lifting objects, feeding, dressing, and writing [1], [2]. In children with hemiplegia, elbow weakness, spasticity, and restricted motion hinder independence and reduce opportunities for participation in both academic and social settings [1], [2]. The inability to effectively use the impaired upper limb not only affects motor function but also impacts self-esteem and social integration.

Traditional rehabilitation for pediatric hemiplegia emphasizes **task-specific and repetitive training** to strengthen motor control and improve functional arm use [3]. However, therapy faces challenges in maintaining sufficient intensity, ensuring adherence to home-based practice, and overcoming the shortage of specialized pediatric therapists in countries like Sri Lanka [2], [3]. Consequently, many children fail to receive adequate therapy dosage needed to promote **neuroplastic reorganization** and long-term motor recovery.

Recent advancements in **Virtual Reality (VR)** and **serious gaming** provide promising alternatives by embedding therapy within motivating, immersive, and child-friendly environments. VR-based interventions have been shown to improve therapy adherence and motor learning outcomes by transforming repetitive tasks into interactive game experiences [3], [8], [9]. Liao et al. [4] demonstrated that VR serious games prolong attention and improve motor engagement, while Brunner et al. [8] reported that gamification significantly enhances pediatric motor outcomes. However, most VR rehabilitation tools focus on gross movements with handheld controllers, neglecting detailed **elbow joint kinematics** critical for functional independence.

**Wearable sensing technologies**, including IMUs and flex sensors, provide a robust and cost-effective solution for capturing elbow motion in real time. Compared to vision-based systems, wearable sensors are more reliable in home environments, as they are less affected

by occlusion or camera placement [7]. Data collected from these sensors can be enriched using **machine learning (ML)** to recognize therapeutic gestures, classify movement quality, and adapt exercises to each child's performance. Studies have shown that Support Vector Machines (SVM) and Long Short-Term Memory (LSTM) networks achieve high accuracy in motion classification, allowing therapy to be both personalized and clinically reliable [6], [7].

Equally important is **sustaining motivation** in pediatric rehabilitation. Research consistently shows that gamification elements such as rewards, adaptive challenges, and fantasy-based narratives enhance adherence and engagement [9], [11]. Sardi et al. [11] highlight the positive impact of gamified systems on participation, while Lewis et al. [10] emphasize the role of parental support in maintaining practice consistency. Incorporating feedback mechanisms—such as **animations, sounds, rewards, and AI-driven encouragement**—can prolong engagement and improve therapy effectiveness [1], [9].

In summary, although VR, wearable sensors, machine learning, and gamification have demonstrated significant potential in pediatric rehabilitation, most existing systems remain fragmented. They either emphasize motivation without clinical precision, or provide biomechanical monitoring without engagement. This project addresses these limitations through the development of an **affordable, VR-based elbow rehabilitation platform** that combines **wearable sensors, ML-powered movement recognition, and tri-layered monitoring (therapist, parent, AI)**. This integrated framework, tailored for children in low-resource contexts such as Sri Lanka, offers a scalable and accessible solution to improve elbow motor recovery in pediatric hemiplegia.

## 3. Literature Review

### 3.1. Clinical context and rehabilitation requirements

Hemiplegia in children is often characterized by unilateral motor difficulties with the upper limb (especially the elbow joint), resulting in weakness, decreased range of motion, and the child's inability to complete important aspects of daily tasks such as reaching, lifting, or carrying [1], [2]. Conventional therapy prior to this and other studies often rely on physiotherapy exercises targeting elbow flexion/extension as well as pronation/supination which can improve motor function. However, due to the lack of pediatric rehabilitation specialists, excessive costs and the distance the family must travel to get to therapy in a country like Sri Lanka, conventional therapy is often inaccessible [2], [3]. Given these challenges, there is a real need for children with hemiplegia to use low-cost and fun rehabilitation solutions that can be implemented at home.

### 3.2. Virtual reality (VR) and serious games as rehabilitation

VR-based rehabilitation is a developing and promising approach to pediatric motor training, allowing rehabilitation providers to improve motivation, adherence and the intensity of practice compared with traditional interventions [1], [3], [8], [9]. The studies show that games in a VR environment can lead to improvement in motor function while keeping children engaged. Brunner et al. [8] completed a systematic review that suggested that serious games can have a meaningful influence on the recovery of upper limb motor function (p. 268), but there is limited high-quality trials in paediatric elbow rehabilitation. Furthermore, Taheri et al. [9], stated that additional benefits were apparent through the use of interactive and immersive game-based therapy which provided enhanced adherence and increased clinical outcomes in the rehabilitation of workers, in their systematic review. This study, among others, emphasized that motivation is an important driver of adherence to rehabilitation amongst children and adolescents.

### 3.3. In the field of elbow rehabilitation, wearable sensing technologies

Inertial Measurement Units (IMUs), specifically the MPU6050 and MPU9250, are quite popular for tracking elbow and upper limb movements due to their ease of acquisition, portability, and accuracy in kinematic data collection [5], [6]. IMUs can measure angular displacement, acceleration, and orientation, and therefore can be utilized to monitor flexion, extension, pronation, supination, and reaching in real time. It has been shown that in home settings, IMUs are more robust than optical motion capture systems, because they require minimal setup, and do not suffer from occlusion difficulty [5], [7].

### 3.4. Machine learning for movement classification

Machine learning algorithms can translate sensor data into meaningful therapeutic feedback. Support Vector Machines (SVM) are appropriate to classify static postures and Long Short-Term Memory (LSTM) networks work well to recognize dynamic movement sequences [6], [7]. Fu et al., [7] conducted a review on ML applications for pediatric hemiplegia rehabilitation and concluded that embedding ML models in wearable systems improves accuracy, personalization, and adaptive design of exercise programs, despite certain limitations (e.g., sensor drift and calibration).

### 3.5. Motivation and Engagement in pediatric Rehabilitation

The incorporation of gamification strategies has been shown to motivate children and maintain engagement in pediatric rehabilitation [3], [8]. Sardi et al., [11] found that using appropriate rewards, adaptive challenges, and narrative immersion led to a greater participation and engagement. Visual and auditory feedback (e.g., glowing effects, sound cues, and progress indicators) reinforce successful movements and support motor learning [1], [8], [9]. Additional, studies show children are more likely to sustain engagement when parents are attentive and supportive in monitoring child's progress [10].

### 3.6. Doctor, parent, and AI-assisted monitoring

Remote monitoring is vital to the sustainability of rehabilitation. Monitoring dashboards allow clinicians to view performance metrics and modify therapy plans while also monitoring progress as parents provide home-based practice [10]. In low-resource settings where ongoing clinical supervision is not possible, AI-enabled voice assistants can provide motivational direction, real-time feedback, and encourage exercise adjustments [9], [11]. The proposed integration of AI to provide an intelligent coaching model combined with wearable sensors and VR platforms ensures continuity in therapy and addresses gaps in access to pediatric rehabilitation services.

**Table 1: Synthesis of Literature and Identification of the Research Gap**

Research Focus	Key Strengths	Key Limitations	Relevance to Our Project
Clinical Context & Rehabilitation Needs	Highlights the functional difficulties in hemiplegic children; emphasizes need for elbow-targeted rehab; shows importance of accessibility in low-resource settings.	Conventional therapy limited by cost, distance, and shortage of specialists in Sri Lanka.	Justifies the need for a <b>low-cost, home-based system</b> that directly addresses elbow function.
VR & Serious Games	Improves motivation, adherence, and therapy intensity; provides immersive, engaging environments; systematic reviews support motor recovery potential.	Limited high-quality trials in pediatric elbow rehab; many systems designed for adults.	Supports our choice of <b>VR-based exercises</b> targeting elbow movements in children.
Wearable Sensors (IMUs)	Low-cost, portable, accurate kinematic data (flexion/extension, pronation/supination); robust in home settings; avoids occlusion issues.	Sensor drift, calibration needs; often used in research/assessment but less integrated into full therapy systems.	IMUs (MPU6050/9250) are practical for <b>real-time elbow motion tracking</b> at home.

Machine Learning for Movement Classification	Enables translation of raw data into meaningful feedback; algorithms (SVM, LSTM) can detect static/dynamic movements; personalization possible.	Sensor errors may affect accuracy; some models complex to deploy in low-resource devices.	ML models allow us to <b>classify elbow motions and provide adaptive, intelligent feedback.</b>
Motivation & Engagement in Pediatric Rehab	Gamification increases adherence; adaptive challenges and rewards sustain engagement; feedback (visual/auditory) enhances motor learning.	Engagement may decline without parental or external support; balance of challenge vs. ability critical.	Guides design of <b>rewarding, adaptive VR tasks</b> that motivate children in long-term use.
Doctor, Parent, and AI-Assisted Monitoring	Remote monitoring dashboards empower clinicians and parents; AI assistants can provide motivational and corrective feedback; extends therapy beyond clinic.	Requires reliable connectivity and careful design to ensure usability in low-resource settings.	Strengthens <b>sustainability and supervision</b> of home rehab by combining AI monitoring and parental involvement.

### 3.7. Conclusion

The existing literature lays a foundation for examination of technology-assisted rehabilitation in pediatric hemiplegia, specifically elbow function. Traditional therapy is not available to many families throughout Sri Lanka, and there is a need for home-based, low-cost alternatives. VR and serious games have demonstrated improvements in motivation and compliance but have been rarely explored in pediatric elbow rehabilitation. Wearable IMU sensors (MPU6050, MPU9250) are an inexpensive and accurate option for tracking movement in non-clinical settings, while machine learning models can make classifications about movement and assess quality of movement. Combining gamification approaches with intelligent feedback and remote monitoring by parents or clinicians should enable continued engagement and therapeutic context. In summary, it is very clear that there is a research gap: There is no child-centered rehabilitation platform that integrates VR, wearable sensing, machine learning, and AI-assisted monitoring solutions into a single platform to provide low-cost therapeutic delivery for children receiving elbow rehabilitation in resource-limited settings.

## 4. Research Gap

VR-based rehabilitation and wearable IMUs have explored many facets of upper-limb rehabilitation, but the majority of fixed, modular, and integrated systems are primarily designed for adults or involve expensive hardware, limiting accessibility for pediatric populations [5], [7], [11]. Although prior studies have introduced VR therapy and IMU-based motion tracking, most existing solutions fail to address the unique rehabilitation needs of children with hemiplegia, where motivation, engagement, and long-term adherence are critical for therapeutic success.

Current systems often suffer from the following limitations:

1. **Limited focus on pediatric rehabilitation** – Most rehabilitation platforms target adults recovering from stroke or injury, with little adaptation to children’s motor and cognitive abilities. Children require engaging, story-driven environments to sustain motivation, which generic rehabilitation games do not provide.
2. **High cost and complexity of existing solutions** – Many VR-based rehabilitation platforms rely on expensive hardware (VR headsets, motion capture systems, robotics), making them impractical for widespread adoption in resource-limited settings or home environments.
3. **Insufficient integration of monitoring and feedback loops** – Existing tools often focus only on patient-game interaction without including **multi-level monitoring** from doctors, caregivers, and AI-driven feedback, which is essential for continuous evaluation and personalization of therapy.
4. **Lack of fine-grained movement analysis** – While some systems track gross arm movements, few provide detailed monitoring of **elbow and finger-level motor control**, which is critical in hemiplegia rehabilitation for restoring functional independence.
5. **Minimal caregiver and parental involvement** – Parental supervision is crucial for ensuring consistent practice in children, yet most platforms neglect structured parental feedback or progress tracking features.
6. **Absence of adaptive motivation mechanisms** – Many rehabilitation games lack **voice-assisted encouragement, adaptive challenges, and narrative-driven rewards**, which are key motivators for children, especially when direct supervision by doctors is unavailable.

The proposed "**Knights Quest: The Shield of Strength**" directly addresses these gaps by embedding therapeutic elbow and finger movements into an **immersive VR narrative game**. Unlike existing systems, this framework:

- Combines **IMU-based sensing** with **ML-driven categorization of movements** for fine motor accuracy.
- Provides **multi-level monitoring** (doctor supervision, parental tracking, and AI-driven motivational feedback).
- Uses **low-cost wearable IMUs** instead of expensive robotic or full-scale VR setups, ensuring affordability and accessibility.
- Leverages **story-driven gameplay and adventure elements** to maintain long-term engagement in children, transforming repetitive exercises into meaningful game actions.
- Generates **automated progress reports** for doctors and caregivers to guide therapy adjustments.

Thus, this system bridges the gap between **clinical rehabilitation requirements** and **engaging pediatric therapy** by integrating medical oversight, parental involvement, and AI-driven motivation into a single, cost-effective, and scalable rehabilitation framework suitable for both clinical and home-based use.

## 5. Research Problem

Going back to the literature review, the following research issues emerged discussed about rehabilitation of pediatric hemiplegia:

1. Most rehabilitation systems for children with hemiplegia are based on a traditional physiotherapy or a more generic game-based intervention to determine the best program for patients, and as some of the systems track or monitor individuals, none adapt to their clinical needs or range of motion restrictions.
2. Most VR or game based rehabilitation systems have the clinician unable to perform real-time assessments or evaluations to inform therapy and adjust it based on the child's real performance.
3. Caregivers tend to be less involved with creating therapy opportunities, despite literature evidence defining the active participation of caregivers improves engagement in therapy and outcomes.
4. None of the systems use AI-generated verbal encouragement and guidance when professional guidance is not available. This is important for maintaining engagement of the patient.
5. Most of the contemporary systems focus largely on Visual Upper limb gross movement kinematics. Some may record elbow joint kinematics, and very few systems have tracking of joint

kinematics of the upper limbs, which represents an opportunity to improve functional use of the arm across many daily activities.

## 6. Research Question

Based off the research problems above, the following research question presents itself:

What intelligent and game-based rehabilitation framework could be developed that provides doctor oversight, parent guidance, and an AI-based voiced enabled assistant to support elbow motor functions in children with hemiplegia?

To answer the above research question, the proposed framework will have the following components:

- Doctor oversight and advice – Clinicians would be able to do remote tracking, quality movement recognition, and therapy readjustment.
- Parental oversight – Parents would be able to see progress dashboards, reinforce compliance, and enable continuous home rehab.
- Voice enabled assistant encouragement – An AI enabled assistant for motivational prompts when a doctor is not attainable.
- Game based therapy with an elbow joint tracking engine – to capture elbow joint motions for flexion, extension, pronation, supination, reaching and embed them into an appealing fantasy/adventure VR based game.
- Progress reporting – the system generates a summative performance report for clinicians and parents to support therapy decisions, and interventions through time.

## 7. Objectives

The long-term goal of this project is to develop, design, and test a gamified, VR-driven rehabilitative system for augmenting upper limb motor function in young children with hemiplegia. The latter will also be achieved through low-cost wearable sensor technology, movement classification via machine learning, and an experiential gaming environment so as to develop an efficient and motivating recovery tool.

### 7.1. General Goal

For creating an inclusive, low-cost, and interactive system of VR-augmented therapy ("ArmiGo"), using IMU sensors and machine learning for enabling and tracking rehabilitative elbow exercises for young hemiplegic patients, and supporting efficient home therapy with clinical monitoring from a distance.

### 7.2. Specified objectives

To develop and deploy a wearable hardware system consisting of an IMU sensor (MPU6050/9250) integrated with an elastic elbow sleeve and an ESP32 microcontroller for precise, real-time monitoring of elbow motion (flexion, extension, pronation, supination, and reach).

To construct an efficient machine learning model capable of predicting and confirming therapeutic elbow motion based on IMU sensor inputs in real-time with at least 85% accuracy, employing algorithms like SVM for static poses as well as LSTM networks for moving sequences of motion.

Develop and design an immersive VR game ("Knight's Quest: The Shield of Strength") on the Unity/Unreal Engine that converts covert elbow movements into relevant game actions with adaptable difficulty level scaling, immediate visual/aural feedback, and storytelling for achieving maximum user participation and motivation.

In aid of establishing a multi-level monitoring and support mechanism comprising:

- A secure cloud clinician dashboard for remote monitoring of progress and adaptation of therapy.
- A caregiver smartphone app for monitoring daily performance and tasks.
- Integrated AI speech system for providing inspirational guidance and commentary for sessions.

- To carry out pilot testing and assessment of the system with a few healthy children and a small group of children with hemiplegia so as to determine its usability, interactivity, and initial efficacy for increasing range of motion and facilitating therapy adherence.

## 8. Outcomes

It will help if the project achieves successful completion as follows:

**A Functional Prototype:** A combined "ArmiGo" system of the wearable sleeve, the functional VR game, and the backend cloud system for data processing and tracking.

**A Validated Machine Learning Model:** A trained and deployed ML model capable of accurately interpreting elbow rehabilitation exercises, providing a foundation for personalized and adaptive therapy.

**A Challenging Therapeutic Game:** A validated and completed VR game that effectively gamifies prescribed elbow movement, facilitating rehabilitation as an enjoyable and motivating experience for children and potentially increasing practice duration and adherence.

**A Remote Monitoring System:** Web and mobile dashboards that allow clinicians to remotely view therapy and permit active involvement of parents during their child's rehabilitation process, bridging the clinic-home gap.

**Pilot Study Results:** Experimental findings of initial user tests which show:

**High Usability:** A very high System Usability Scale (SUS) score which reflects the system as very intuitive and easy for children and caregivers to use.

**High Engagement:** Long session times, regular use, and beneficial user feedback.

**Preliminary Efficacy:** Temporary restoration of range of motion, precision of movement, and use of the affected arm for its intended function.

**A Cost-Effective Solution:** A proof-of-concept of an affordable rehabilitation system using off-the-shelf, low-cost devices, facilitating advanced therapy for resource-impooverished environments like Sri Lanka.

**Academic Contribution:** A cumulative body of scholarship contributing value-added content to the fields of medical VR, wearable sensor technologies, and pediatric rehabilitation, potentially leading to publishable scholarly achievements.

## 9. Methodology

The proposed elbow rehabilitation system has a defined methodology promoting technical strength, clinical relevance, and usability in a low-resource environment like Sri Lanka. The development consists of seven stages; sensor selection & hardware design, data collection & preprocessing, machine learning model, VR game incorporation, real time feedback, communication with doctors & parents, and evaluation. Each stage is designed to directly assist hemiplegic children go through gamified VR therapy.

### 9.1. System Overview

#### 9.1.1. Component Overview

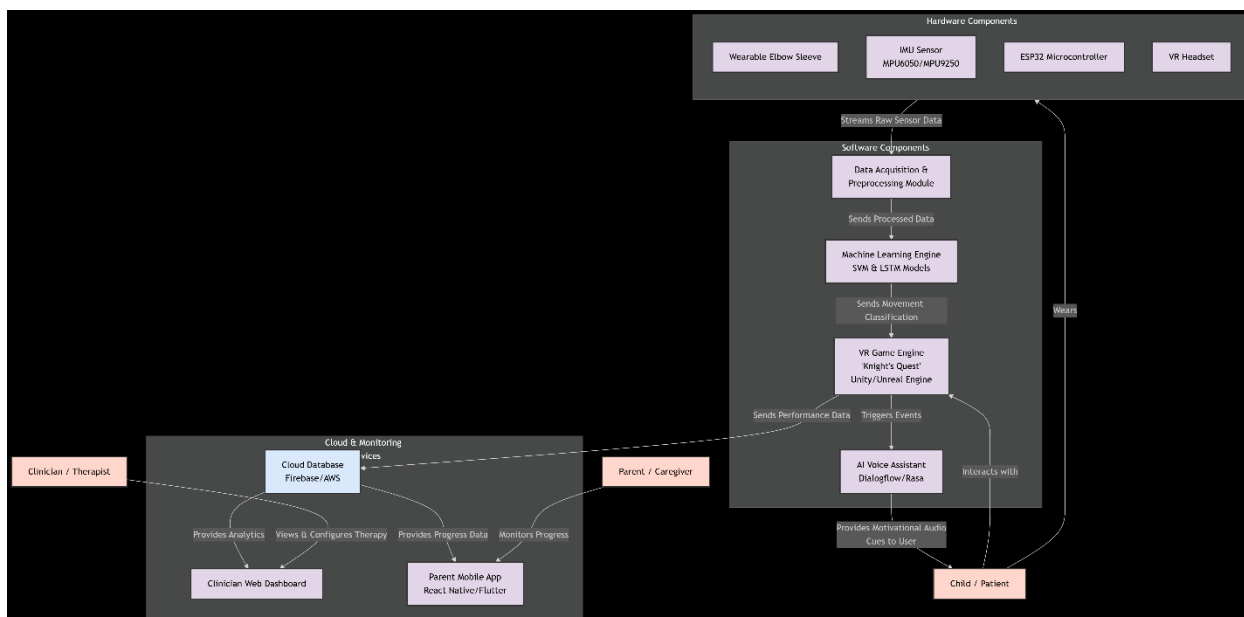


Figure 1: Component Overview

## 9.2. Component Used

### 9.2.1. Sensor selection and hardware design

The system is based on a wearable elbow sleeve that contains IMU sensors (MPU6050 or MPU9250) to measure acceleration and angular velocity. IMUs are a suitable sensor because they have been economically affordable, accurate, and have been shown to work in previous upper limb rehabilitation approaches [5] [6]. Sensors are affixed to an elastic sleeve in a fixed position, ensuring they are stable during exercise, but do not impede full range of motion.

We used an ESP32 microcontroller for real-time data acquisition and wireless transmission, allowing it to be integrated into the VR environment, while only tracking elbow movements of interest (flexion, extension, pronation, supination, reach / lift). We set angular positions at baseline and the dynamic range of movements through calibration of the sensor, customizing rehabilitation for each child. The hardware was engineered to be lightweight, safe, and suitable for use in the clinic or home [7] [9].

### 9.2.2. Data Collection and Data Preprocessing

Data collection involves recruiting typically developing children to perform standardized elbow movements to generate normative reference ranges. Also, data from the unaffected arm of children with hemiplegia are also recorded to provide individualized reference ranges [2], [6].

Raw IMU signals can be noisy and therefore Kalman filtering and moving average smoothing are both provided high-pass filters to reduce noise. Data is segmented into discrete windows relating to a particular arm movement, and labeled for machine learning. Some of the possible features extracted are angle displacement, velocity and orientation data, and time series motion patterns, so a robust dataset can be used to train the IML models [7], [8].

### 9.2.3. Machine Learning Model Development

Machine learning is used to classify the movement of the elbow to provide real-time therapeutic feedback.

- Static gesture recognition: Support Vector Machines (SVM), classify postures, such as holding the elbow at a certain flexion angle [7].
- Dynamic gesture recognition: Long Short-Term Memory (LSTM) networks capture sequences of actions, such as repeated lifting or rotational movements [7], [8].

The dataset is divided into a training (70%), validation (15%), and testing (15%) dataset, and k-fold cross-validation is applied to minimize overfitting. Performance is measured by accuracy, precision, recall, F1-score, and confusion matrices. All models are optimized during development

for translation onto the ESP32 and VR platform via TensorFlow Lite or ONNX for low-latency recognition while playing [7], [8].

#### 9.2.4. Virtual Reality Game Design and Integration

Rehabilitation exercises are woven into a gamified VR environment dubbed "Knight's Quest: The Shield of Strength." In the narrative game, each elbow motion has corresponding in-game action:

- Flexion: Raise the knight's sword
- Extension: Strike adversaries or push aside obstacles
- Pronation/Supination: Rotate or direct a magical shield
- Reaching/Lifting: Grab treasure or activate magical artifacts

Adaptive difficulty sets up opportunities for progressive challenge: as the child gets better, the exercises require them to hold finishes for longer periods, execute strikes faster, or complete more complex motion sequences. If fatigue and errors during to performance increase, the difficulty may decline to maintain engagement. The game can be developed and delivered through Unity3D or Unreal Engine, so it can work with inexpensive VR headsets, providing for use in low-resource international settings [4], [9], [10].

#### 9.2.5. Feedback and Motivation Live

Live feedback is given to reinforce successful movements and keep children engaged:

- visual signals: sword glow, shield aura, treasure shimmer.
- audio signals: upbeat narration, cheer sounds and verbal prompts.

Emotionally adaptive gameplay adapts the difficulties according to performing metrics, including unprompted actions or movement slowness. The AI voice assistant provides to continuous encouragement, encouraging children to remain engaged even though the educator may be away [2], [10], [11].

### 9.2.6. Doctor and Parent Monitoring

A multi-level monitoring ecosystem enables remote supervision:

- Doctors: Secure cloud access to IMU and gameplay data allows evaluation of progress, gesture quality, and therapy adjustments. Tele-consultation supports real-time guidance [6], [10].
- Voice Assistant: Provides guidance and motivation when a clinician is unavailable.
- Parents: A mobile caregiver dashboard displays daily completion, movement accuracy, and in-game achievements, enabling active involvement in home-based therapy [10], [11].

This ensures continuous support, even in low-resource settings, and strengthens home-clinic rehabilitation integration.

### 9.2.7. Evaluation and Deployment

Initial usability, engagement, and therapeutic effectiveness has been established with healthy and hemiplegic children through pilot testing. Some clinical metrics are:

- Elbow range of motion improvement
- Reduction in time of task completion
- In game/exercise score improvements
- Therapy adherence rate

Usability will be evaluated by the System Usability Scale (SUS), and stakeholder feedback from caregivers. Engagement metrics will include session duration, number of sessions and progression in observed game difficulty. Clinical usability was optimized for hardware affordability; killer applications such as ESP32, IMUs and inexpensive VR headsets allow continued engagement in clinical and home-based situations in Sri Lanka [2], [5], [9].

### 9.3. Technologies

The implementation of the proposed elbow rehabilitation system is contingent upon a well-conceived technology stack that incorporates hardware, firmware, data processing, machine learning, game development, cloud services, mobile interfaces and AI-supported services. The key design objective is to ensure that system components can be integrated to produce a fun and enjoyable rehabilitation experience for children while simultaneously maintaining affordability, scalability, and clinical relevance in low-resource environments such as Sri Lanka.

#### 9.3.1. Hardware Layer

At the hardware level, the foundation of the system is the ESP32 microcontroller, which offers a cost-effective, compact device with built-in Wi-Fi and Bluetooth connectivity. Its processing speed is satisfactory for real-time biomedical applications such as developing motion tracking for pediatric rehabilitation [7]. The ESP32 microcontroller can interface with IMU sensors such as the MPU6050 or MPU9250, fixed onto the child-friendly elastic sleeve to capture acceleration, angular velocity, and orientation for flexion, extension, pronation, supination, and reaching movements [5], [6]. Instead of employing rechargeable batteries, we would rely on a simple breadboard-based power distribution arrangement that would enable continuous operation safely, while male-female jumper wires would provide stable connections between system components while the system is tested and developed. The system also can facilitate low-cost VR headsets such as Google Cardboard or Oculus Quest, which have been reported to have clinical applications in immersive pediatric rehabilitation [4], [9].

#### 9.3.2. Firmware and Data Handling Layer

The firmware and data handling layer is developed with Arduino IDE and MicroPython, convenient platforms for IoT and biomedical prototyping [7]. They control the IMU sensors, preprocess motion signals, and send data through serial or Wi-Fi communication protocols with a minimal delay. During this data logging phase real-time noise filtering techniques including Kalman and moving average filters reduce noise in the raw sensor signal and help smooth any inaccuracies in measuring elbow movement which is important for accurate therapy [7].

#### 9.3.3. Machine Learning Layer

Machine Learning underpins personalizing therapy. Support Vector Machines were used to classify static postures (such as flexed or extended positions) and Long Short-Term Memory (LSTM) networks were utilized to develop temporal dynamics of sequential movements (such as repeated pronation, supination, and lifts of the participants' upper extremities)[3], [7], [8]. The

various models were created in Python and optimized for light deployment environments using TensorFlow Lite or Open Neural Network Exchange (ONNX). This process was used to develop a lightweight deployable format for real-time classification of gestures through the ESP32 microcontroller and insertion into the VR environment. The use of Kalman filters and moving average smoothing techniques were implemented as preprocessing techniques to stabilize the signal and improve classification accuracy[7].

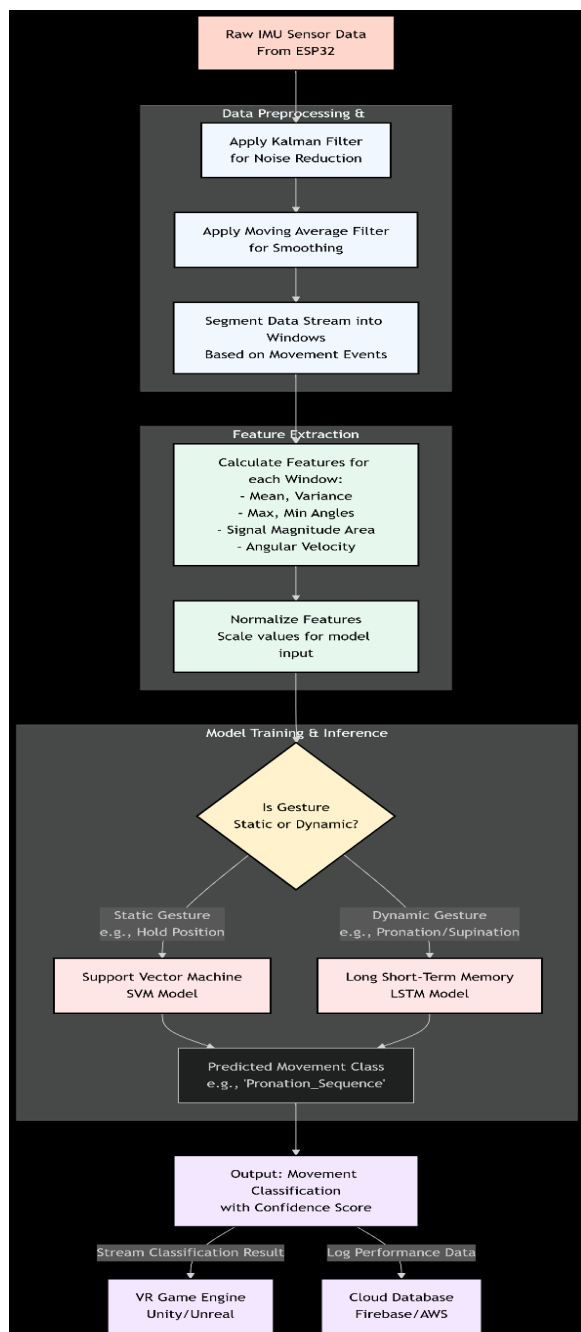


Figure 2: Data Processing Diagram

### 9.3.4. Game Development Layer

In the game development layer, rehabilitation exercises are integrated into a VR environment, "Knight's Quest: The Shield of Strength." This narrative game transforms every movement of the elbow either by flexion, extension, or rotation into a motivation act of play in the VR environment. The flexion of the elbow allows the user to raise sword. The extension allows for striking/pushing obstacles. The pronation/supination rotates a shield. The reaching movements allow for picking up treasures. The games is able to automatically calculate adaptive difficulty scaling so as the child gets better at performing a motion the game properly challenges the child's goal of improving their skills while staying engaged but not so frustrated (see [4], [9], [10]). Each of these dimensions are important influences on the overall play value of the VR game. The VR game is implemented inside either Unity3D or Unreal Engine where reasonable priced VR headsets are compatible with the resources found in low-resource settings.

### 9.3.5. Cloud and Monitoring Layer

The cloud and monitoring layer provides remote access to rehabilitation data for doctors and caregivers. They can use platforms like Firebase or AWS to securely store all of the session data, as well as have access to a visualization dashboard of a clinician view that contains metrics about movement quality, trends in progress, and therapy adherence [6], [10]. This remote monitoring decreases the barriers potential physiotherapists would experience related to access to a specialized pediatric physiotherapist.

The mobile and caregiver interface is developed with cross-platform K-frameworks like Flutter or React Native and is developed to support parent engagement in tracking daily participation and any improvements in elbow range of motion, and provide encouragement [10], [11]. The notifications and summary analytics foster everyday practice and strengthen the link between rehabilitation at home and in the clinic.

Finally, the AI-enabled support layer has a voice assistant which is used through platforms such as Dialogflow or Rasa to improve participant interaction and the AI app's capabilities to provide real-time, interactive support, motivational comments and playful anecdotes when a clinician is not available [2], [9], [10]. This layer ensures that therapeutic continuity continues, supporting timely interventions and lowering dropout rates. In the case of clinicians being available, the teleconsultation feature permits others to directly monitor and supervise continuously improving this hybrid form of human-AI monitoring.

In summary, this multi-layered technology stack provides low latency, clinical efficacy, and flexibility. The technology stack setup has flexibility to support integrating future innovations such

as haptic feedback, advanced AI personalization, and expanded sceneries for VR rehabilitation in aligned with the global trends for gamification therapy for motor impairments [3], [7], [8].

## 10. Functional and Non-Functional Requirements

### 10.1. Functional Requirements

The elbow rehabilitation system is designed with functional requirements for clinical relevance, usability, and effectiveness:

#### 10.1.1. Real-Time Elbow Motion:

The system must track the motion of the elbow joint in real-time using IMU sensors (MPU6050/MPU9250) fixed to an elastic sleeve and connected to an ESP32 microcontroller. The movement tracked includes flexion/extension, pronation/supination, and reaching/lifting. Real-time tracking also allows the potential for precise assessments of motor function and progress of rehabilitation [5], [6], [7].

#### 10.1.2. Gesture Recognition and Rehabilitation Exercises:

The system must classify and recognize therapeutic elbow movements from the sensor using machine learning models (SVM will be used for recognizing static postures while LSTM will be used for recognizing dynamic sequences). The therapeutic movements will be mapped to corresponding actions in a VR game to ensure the child can perform the exercises correctly while being engaged [7], [8].

#### 10.1.3. Virtual Reality (VR) Game-Based Rehabilitation:

The system is required to provide an immersive VR experience (called "Knight's Quest: The Shield of Strength") where elbow movements are linked directly to actions in the game. For example, flexion will lift the sword, extension will hit enemies or push obstacles, pronation/supination will rotate the shield, and reaching/lifting will collect treasures. The benefits of VR gamification in pediatric rehabilitation include increasing patient engagement, promoting neuroplasticity (the brain's ability to rewire itself), and improving motor learning opportunities [2], [4], [9], [10].

#### 10.1.4. Remote Monitoring and Clinician Dashboard:

The system is required to provide a secure cloud-based platform that will allow clinicians to monitor the patient's performance, track progress metrics, and modify therapy plans as is necessary. This capacity to remotely monitor patient adherence and results can facilitate continuous care for children unable to regularly attend a rehabilitation center [2], [6], [8].

#### 10.1.5. Caregiver and Patient Support Interface:

A mobile application is required for the caregivers that will allow for reminders for the sessions, diagrams of the child's progress, motivational messages, and adherence tracking. It is recognized that active participation of the caregiver positively benefits adherence and rehabilitation outcomes [5], [10].

### 10.2. Non-Functional Requirements

#### 10.2.1. Accuracy of Motion Tracking:

The IMU based tracking and machine learning classification models must achieve at least 85% accuracy in detecting and classifying elbow rehabilitation movements. Clinical research indicates that reliable outcomes require accuracies above 80% [5, 7].

#### 10.2.2. Reliability and low latency:

The system must support low latency transport of the sensor data to the virtual reality game and cloud. Latencies greater than 100 ms could negatively impact the immersive experience for the user, regardless of the effective impact on rehabilitation [4].

#### 10.2.3. Scalability and Cost:

The system should be able to be built in a modular and easily extensible way to allow adding more sensors, new virtual reality scenarios, or new artificial intelligence modules without needing major upgrades to hardware. The use of ESP32's, low-cost IMU's and low-cost virtual reality headset support multiple levels of access in under-resourced places such as Sri Lanka [5, 8].

#### 10.2.4. Usability and Engagement:

The system should provide a child-friendly, intuitive, and motivating experience. Engagement is very important in pediatric rehabilitation, especially when the exercises are repetitive, and the child is asked to focus for more than a few minutes [2, 4, 9, 11].

### 10.2.5. Security and confidentiality of data:

All patient and caregiver data must be transmitted and stored securely, and it must be encrypted. The system must comply with data protection standards (e.g., HIPAA, GDPR) in order to keep the clinician and caregivers trust [2, 6].

## 10.3. User requirements

### 10.3.1. For Children (Patients)

- **Engaging and Motivating Experience:**

The system should provide fun and immersive VR-based games that make elbow rehabilitation enjoyable, keeping children motivated to practice consistently.

- **Intuitive Controls:**

Elbow movements must directly translate into game actions, allowing children to interact naturally without requiring complex instructions.

- **Immediate Feedback:**

The system should deliver real-time visual and auditory feedback to let children know when their elbow movements are correct or need adjustment.

- **Adaptive Difficulty:**

The VR games must automatically adjust challenge levels based on the child's progress to maintain therapeutic effectiveness while preventing frustration.

- **Safe and Comfortable Use:**

Wearable devices, sensors, and VR equipment must be lightweight, ergonomic, and safe for prolonged use during therapy sessions

### 10.3.2. For Caregivers/Parents

- **Progress Monitoring:**

The system should provide simple and clear progress reports, helping parents track their child's improvement in elbow movement over time.

- **Session Management:**

Caregivers should receive reminders about therapy schedules and be able to ensure their child follows the prescribed rehabilitation routine.

- **Guidance and Support:**

The system should notify caregivers if exercises are performed incorrectly, allowing them to assist the child in real time.

- **Remote Assistance:**

Caregivers should have the option to connect with clinicians via the system's dashboard to clarify doubts or seek support when needed.

### 10.3.3. For Clinicians/Therapists

- **Remote Monitoring and Analysis:**

Clinicians must be able to remotely access detailed patient data, including elbow movement ranges, accuracy, and exercise adherence.

- **Customizable Therapy Plans:**

Therapists should have the ability to adjust game settings, exercise routines, and levels of difficulty according to each child's therapeutic needs.

- **Integration of Analytical Insights:**

The system should include performance analytics to highlight progress trends, movement quality, and areas that need improvement, supporting clinical decision-making.

- **Data Security and Compliance:**

All patient data should be securely stored and comply with healthcare privacy standards, ensuring safe use of remote rehabilitation.

# 11. Project Commencement

## 11.1. Work Breakdown Structure

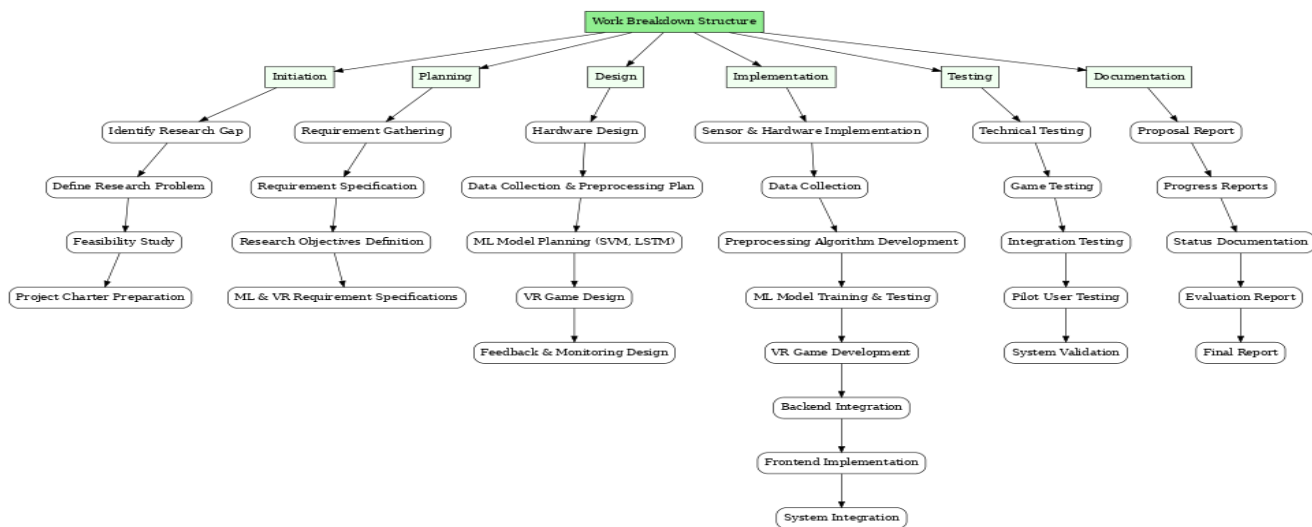


Figure 3: Work Breakdown Structure

## 11.2. Gantt Chart

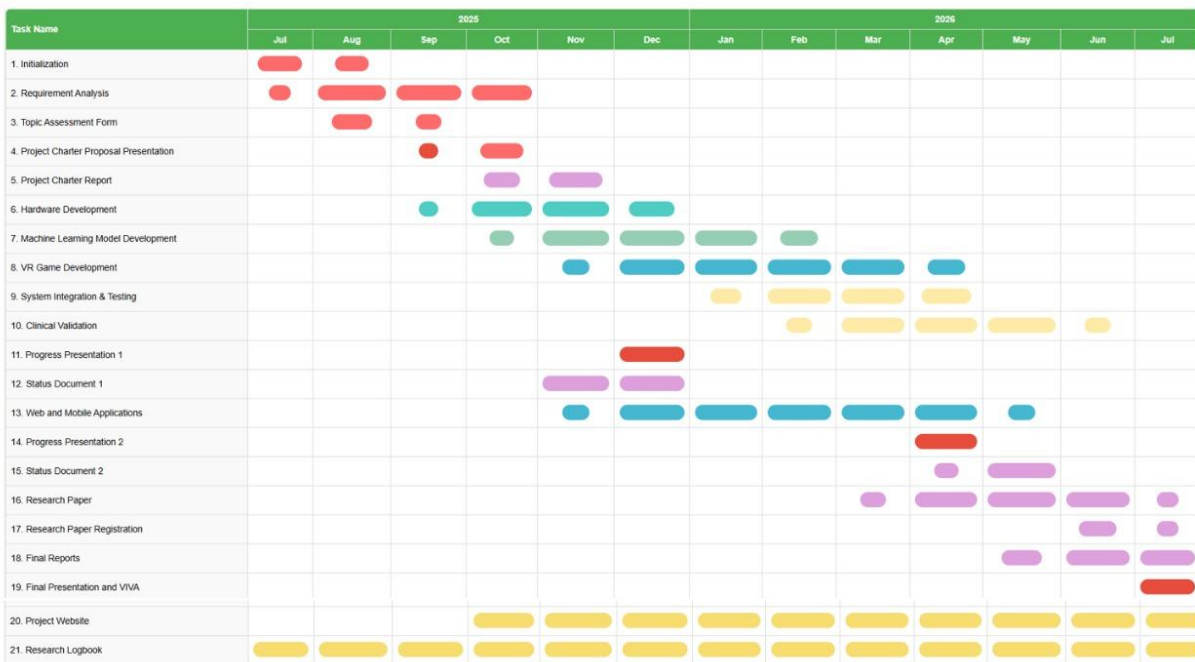


Figure 4 : Gantt chart

## 12. Commercialization

The primary intended users of the planned elbow rehabilitation system would be pediatric rehabilitation centers, clinics and hospitals which employ pediatric rehabilitation therapy for children with hemiplegia or other upper-limb motor impairments in therapy. The system is a cost-effective and portable and fun rehabilitation system for both clinical and home use [2],[5].

Other possible markets and user group considerations:

- Home-based caregivers and parents: Families looking for a safe, motivating and convenient way to rehabilitate children at home while decreasing the necessity to travel to therapy centers regularly [2],[6].
- Pediatric physiotherapists and occupational therapists: Professionals who will benefit from an objective monitoring, program and patient remote management tool [7],[8].
- Educational institutions and therapy centers: Schools or centers that provide therapeutic programs specifically for children with motor disabilities. This can be incorporated into either the educational program for therapy, or the recreational portion of the program where kids can play games [4],[9].
- Research Institutes and universities: Research institutes or universities studying pediatric rehabilitation, biomechanics, applications of wearable sensors, or gamified therapy methods can use the system for experimental study designs or longitudinal studies [5],[7].
- Tele-rehabilitation service providers: Companies or start-ups that provide remote therapy services can utilize the system to offer greater service coverage, particularly in areas with few pediatric rehabilitation specialists [2],[6],[8].

The hardware components of the system (the IMU sensor, ESP32, and VR headset) are upgradable but inexpensive and designed to be expanded to accommodate larger populations.

## 13. DESCRIPTIONS OF PERSONAL AND FACILITIES

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

### 13.2. Facilities

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

## 14. High Level Diagram of the overall System

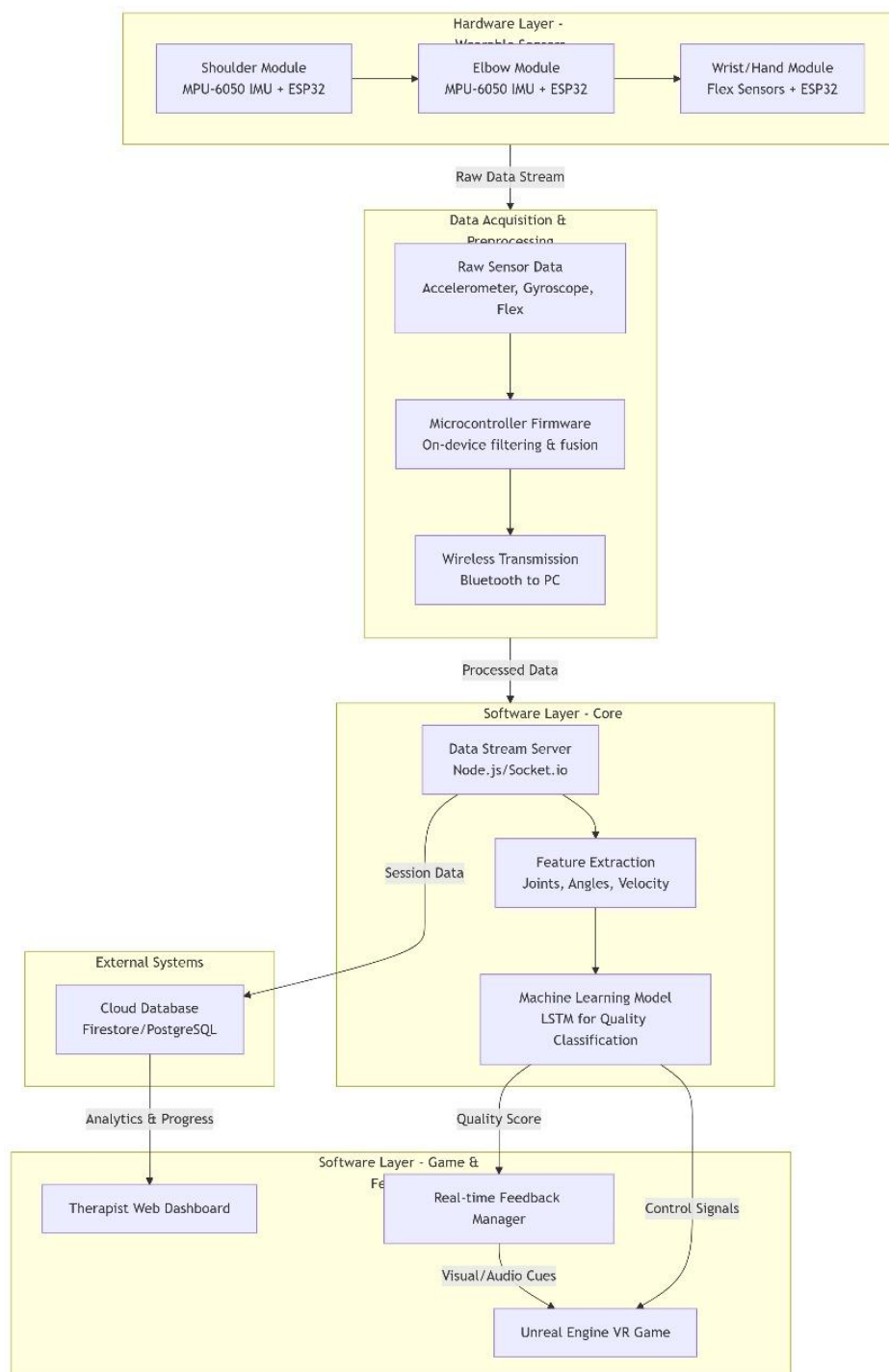


Figure 5: High Level diagram of the System

## 15. Reference

- [1] A. Novak, A. Morgan, and S. Fahey, “Upper limb function in children with hemiplegia: Impact on daily activities,” *Dev. Med. Child Neurol.*, vol. 61, no. 8, pp. 891–898, 2019.
- [2] S. K. Chen et al., “Elbow joint rehabilitation in pediatric hemiplegia: Challenges and outcomes,” *Pediatr. Phys. Ther.*, vol. 31, no. 3, pp. 152–160, 2019.
- [3] J. C. Rosenbaum and D. Stewart, *Cerebral Palsy: Clinical Management and Rehabilitation*, 2nd ed., Springer, 2018.
- [4] T. Hinchliffe, “Virtual reality gamification for pediatric rehabilitation,” *The Sociable*, Jul. 2017. [Online]. Available: <https://sociable.co/technology/therapy-gamification-india>
- [5] B. Yang, H. Zhang, and F. Liu, “IMU-based motion tracking for upper limb rehabilitation: A review,” *IEEE Access*, vol. 7, pp. 114097–114109, 2019.
- [6] S. Patel, H. Park, P. Bonato, L. Chan, and M. Rodgers, “A review of wearable sensors and systems with application in rehabilitation,” *J. Neuroeng. Rehabil.*, vol. 9, p. 21, 2012.
- [7] M. J. Fu et al., “Home-based functional rehabilitation using ML and wearable sensors for children with hemiplegia,” *IEEE Trans. Neural Syst. Rehabil. Eng.*, vol. 28, no. 6, pp. 1461–1470, Jun. 2020.
- [8] R. A. Calabrò et al., “Gamified upper limb rehabilitation using machine learning and VR,” *IEEE Rev. Biomed. Eng.*, vol. 16, pp. 40–55, 2023.
- [9] K.-L. Liao et al., “Virtual reality serious game design for upper limb rehabilitation,” in *Proc. IEEE Int. Conf. Serious Games & Applications for Health (SeGAH)*, 2021, pp. 1–5.
- [10] M. Elsaeh et al., “Haptic VR therapy for pediatric hemiplegia: Pilot study,” in *Proc. Int. Conf. Virtual Rehabilitation (ICVR)*, 2017, pp. 1–6.
- [11] M. Elsaeh, M. Djemai, P. Pudlo, et al., “Quality and quantity assessment in home-based therapy for hemiplegic children,” in *Proc. 6th Int. Conf. Control Eng. & Info. Tech. (CEIT)*, 2018, pp. 1–7.
- [12] T. Hinchliffe, “Indian entrepreneur creates virtual rehab through therapy gamification,” *The Sociable*, 2017.
- [13] S. Patel et al., “Wearable and interactive VR solutions for pediatric rehabilitation,” *J. Med. Eng. Technol.*, vol. 43, no. 7, pp. 382–394, 2019.
- [14] R. A. Calabrò et al., “Toward engaging upper limb rehabilitation: A review of gamified interventions,” *IEEE Rev. Biomed. Eng.*, vol. 16, pp. 40–55, 2023.

## 16. Appendix

