ARMIGO: WEARABLE SENSOR-DRIVEN VIRTUAL REALITY GAME SYSTEM FOR ELBOW REHABILITATION IN PEDIATRIC HEMIPLEGIA

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DECLARATION OF THE CANDIDATE AND SUPERVISOR

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ABSTRACT

Hemiplegia in children, often resulting from perinatal stroke or cerebral palsy, typically affects upper 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 and 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.

Keywords: Hemiplegia, IMU Sensor, Machine Learning, Virtual Reality, Gamification, Pediatric Upper Limb Therapy

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LSTM – Long Short-Term Memory

1. INTRODUCTION

Hemiplegia in pediatric patients, typically a result of perinatal stroke or cerebral palsy, is defined by weakness or partial 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, 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].

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 each 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 into the VR environment which provides motivational suggestions, playful cues, and encouragement when doctors are not available [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, a 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.

1.1 Background and Literature Survey

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.

1.1.1 Clinical context and rehabilitation requirements

Hemiplegia in children usually entails motor problems of the upper extremity especially the elbow joints, causing weakness, limitation of motion and making it difficult for children to perform certain functions of activities of daily living such as reaching, lifting and carrying [1], [2]. Traditional treatment methods consist of physiotherapy treatment, involving elbow flexion and extension movements, as well as pronation and supination movements which are beneficial in increasing motor control [2], [3]. Unfortunately, owing to the unavailability of children's rehabilitation experts, high cost and distance barriers from the patient’s residence to therapy centers, traditional treatments cannot be achieved [2], [3]. It is therefore necessary for children suffering from hemiplegia to have an affordable and motivating rehabilitation approach.

1.1.2 Virtual reality (VR) and serious games as rehabilitation

Virtual reality-based rehabilitation offers a novel approach to pediatric motor training, enabling practitioners in this field to boost motivation, adherence, and practice intensiveness compared with conventional methods [1], [3], [8], [9]. Evidence suggests that games in virtual reality environments enable the improvement of motor skills among children and maintain their interest. According to Brunner et al., [8], there is sufficient evidence that serious games significantly contribute to recovery from injuries in the upper extremities. However, there is a lack of high-quality randomized trials in the field of pediatric elbow rehabilitation. Taheri et al. [9] found that the additional benefits of using such rehabilitation tools included better patient engagement and clinical outcomes, as well as the fact that motivation plays an essential role in encouraging adherence to treatment.

1.1.3 In the field of elbow rehabilitation, wearable sensing technologies

Inertial Measurement Units (IMUs) are very common devices used for tracking elbow and upper body joint motions owing to their convenience, portable nature, and precise kinematics measurement capabilities [5], [6]. IMUs have the capacity to measure angular position, acceleration, and orientation; thus, they can be employed to assess flexion, extension, pronation, supination, and reaching in real time. There have been reports that IMUs work better than optical systems in home environments owing to their lack of setup requirements and occlusion issues [5], [7].

1.1.4 Machine learning for movement classification

Machine Learning (ML) techniques can be used to interpret sensor information and provide useful feedback to the patient. SVMs are effective for classifying stationary positions, while LSTM neural networks can be used to detect dynamic motion patterns [6], [7]. In their systematic review study on the applications of ML for the rehabilitation of children with hemiplegia, Fu et al. [7] found that integrating ML techniques into wearable devices enhances precision, customization, and adaptation of training programs, although some limitations exist.

1.1.5 Motivation and Engagement in Pediatric Rehabilitation

Gamification strategies have been proven to motivate children and increase engagement during pediatric physical therapy sessions [3], [8]. In a study done by Sardi et al., [11], participants were motivated and engaged when rewards, adaptability, and narrative elements were used. Visual and auditory feedback, like lights and sounds, encourage children to perform correctly and help them learn [1], [8], [9]. Furthermore, studies suggest that children tend to engage more actively when their parents monitor them properly [10].

1.1.6 Doctor, parent, and AI-assisted monitoring

Remote monitoring is essential for the sustainability of rehabilitation practices. Dashboards used for monitoring can help healthcare professionals analyze the performance levels and adjust the treatment plan for the patient, along with the ability of the parents to assist at home [10]. For remote locations where constant supervision by the professional is impossible, the use of artificial intelligence-powered voice assistants can act as coaches to the patients, providing them with motivation and feedback as well as helping make exercise changes [9], [11].

1.2 Research Gap

Despite many advantages associated with VR-based rehabilitation and wearable IMUs, most fixed, modular, and integrated systems are designed either for adults or use costly equipment, thereby restricting their utilization among pediatric patients [5], [7], [11]. Although there have been attempts to introduce VR therapy and motion tracking based on IMU in previous studies, none of the approaches consider the special characteristics of upper limb rehabilitation among children with hemiplegia, which are dependent on motivation and patient adherence to therapy.

The shortcomings of currently used technologies are as follows:

1. Inadequate development of tools suitable for children – The overwhelming number of rehabilitation platforms are oriented towards the recovery process of adults who have suffered a stroke or other forms of injuries. For kids, it is crucial to engage them through storytelling; however, current rehabilitation games cannot provide that advantage.
2. Expensive hardware – Some of the available rehabilitation platforms include costly hardware (VR headset, motion tracking technology, robotics), making them unaffordable for a wide variety of users.
3. Lack of monitoring and feedback tools – Current rehabilitation platforms emphasize only interaction between the patient and the game, omitting the need for multi-level feedback mechanisms (doctors', parents', and AI-based feedback).
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 "Knight’s 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 in 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.

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 **low-cost, home-based system** 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 **VR-based exercises** 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 **real-time elbow motion tracking** 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 **classify elbow motions and provide adaptive, intelligent feedback**.
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 **rewarding, adaptive VR tasks** 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 **sustainability and supervision** of home rehab by combining AI monitoring and parental involvement.

ArmiGo: Competitive Analysis

Existing System / Product	Shortcomings / Limitations	Our Solution (ArmiGo)
Hocoma Armeo (Spring / Senso)	Large exoskeleton, very expensive, clinic-only, limited child usability	Lightweight IMU sleeve—- portable, affordable, child-triendly
SaeboVR	Adult-focused, Kinect-based, not elbow-specific, limited pedātric	Pediatric VR game (Knight's Quest) with adaptive elbow rehab
Jintronix	General upper-limb rehab, mostly for adults, limited gamification	Gamified VR with storytelling designed for children
MIRA Rehab	Exergames but not elbow-targeted, lacks doctor/caregiver real-time	Doctor dashboard + caregiver app for remote progress tracking
MindMaze MindMotion PRO	Hospital-based, costly, designed for strokeladults, not home-usable	Home-based rehab using low-cost sensors and VR
Neofect (RAPAEL) Smart Glove	Focuses on hand/wrist, not elbow rehab, expensive	Elbow-specific motion tracking (flexion, extension, pronation, supi-
Flint Rehab FitMi	Covers general arm training, but not pediatric or elbow-focused	Elbow-targeted pediatric therapy with ML accuracy ≥ 86%

1.3 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 the 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 the 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.

1.4 Research 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 to develop an efficient and motivating recovery tool.

1.4.1 Main objectives

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.

1.4.2 Specific 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 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:

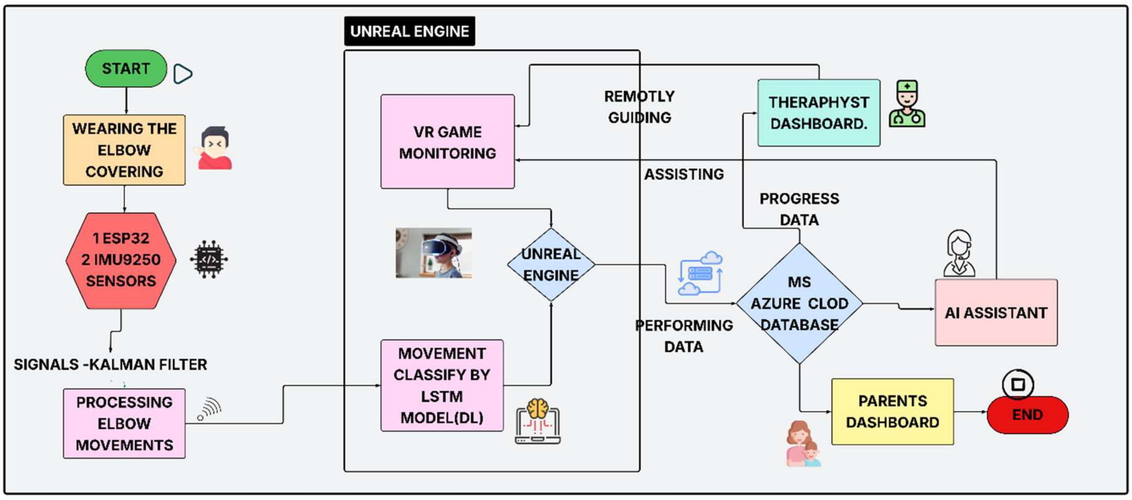
- A secure cloud clinician dashboard for remote monitoring of progress and adaptation of therapy.
- A caregiver smartphone app for monitoring daily performance and tasks.
- Integrated AI speech system for providing inspirational guidance and commentary for sessions.

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

2. METHODOLOGY

The suggested elbow rehabilitation method is based on the methodology that supports the creation of a product with technical robustness, practical application, and user-friendliness for underprivileged regions such as Sri Lanka. The process of developing the method involves seven phases: choosing the sensors and hardware, gathering the data and pre-processing, creating the machine learning model, connecting the virtual reality games, providing feedback, communicating with doctors and parents, and evaluating the performance.

2.1 Understanding the key pillars of the research domain



2.1.1 Sensor selection and hardware design

A microcontroller named ESP32 was chosen for the acquisition of live data and wireless transmission because of its low cost, compact size, and Wi-Fi and Bluetooth functionality that facilitate smooth integration with the VR setup. The device senses movement of the elbow joint during flexion, extension, pronation, supination, and lifting/ reaching, where the initial angular positions and dynamic range of movements are calibrated based on patient-specific criteria. The hardware design was aimed at producing a lightweight, safe, and portable unit that can be used clinically or at home [7], [9]. The motion sensor uses a 9-axis sensor technology, comprising a 3-

axis accelerometer, a 3-axis gyroscope, and a 3-axis magnetometer to measure motion, and calculates the angular velocity as:

$$\omega = d\theta/dt$$

where ω is angular velocity, θ is joint angle, and t is time. The accelerometer measures linear acceleration as:

$$a = dv/dt$$

where a is acceleration and v is velocity. Joint orientation is then calculated using a complementary filter:

$$\theta = \alpha(\theta\_gyroscope) + (1 - \alpha)(\theta\_accelerometer)$$

where α is the complementary filter constant. This sensor fusion approach improves motion accuracy by reducing noise in the raw sensor signals.

2.1.2 Data Collection and Data Preprocessing

The data collection process comprises the recruitment of normal healthy kids and asking them to do standard elbow movements to form normative reference ranges. Also, data is collected from the healthy part of hemiplegic kids to provide individual reference ranges [2], [6]. Training data is acquired from both normal and hemiplegic kids, and the data set includes IMU accelerometer, gyroscope, flex sensors, and joint angles. The IMU sensor signal is often noisy; hence, Kalman filtering is used to smooth these sensor signals to remove the noise. Kalman filtering uses the combination of motion predictions and observed sensor readings to estimate the motion and state update can be expressed as:

$$\hat{x} = Ax + Bu + w$$

The filtered estimation value can be computed via the following equation:

$$\hat{x} = \hat{x} + K(z - H\hat{x})$$

By applying Kalman filtering, random noise is reduced in IMU and analog sensors, yielding reliable motion values that contribute to more accurate motion identification and machine learning classification. Moving average filtering is used in addition as a second high-pass filter to eliminate noise. Data is segmented into windows associated with specific arm motions, and labeling is done for machine learning purposes. Angle change, velocity, orientation data, and motion pattern sequences are among the features identified, allowing for comprehensive data sets for machine learning models [7], [8].

2.1.3 Machine Learning Model Development

Classifiers are employed to recognize the classification of arm movements and give feedback. The machine learning algorithm ARMIGO adopts the use of LSTM Networks as the main classifier of movements, since LSTMs can be used effectively on time series data collected through wearable sensor devices. Moreover, SVM is used for static gestures classification.

Static Gesture Recognition: The static gestures include the postures of having the elbow bent at flexion angles [7].

Dynamic Gesture Recognition: Dynamic gestures include the sequences of performing exercises like continuous lifting or rotation [7], [8].

The LSTM cell output is described with the equation:

$h = o \cdot \tanh(C)$

where h is the hidden state of the cell, C is the memory cell state, and o is the output gate. The LSTM network learns time-series patterns in rehabilitation exercises, recognizes exercises, assesses movements, and detects incorrect postures. The exercises are classified as correct, compensatory, and incorrect.

For model training and evaluation, k-fold cross-validation is performed, with a split ratio of 70%, 15%, and 15% in training, validation, and testing sets, respectively. Evaluation metrics are accuracy, precision, recall, F1-score, and confusion matrix.

2.1.4 Virtual Reality Game Design and Integration

Rehabilitation training exercises are embedded into a game world called "Knight's Quest: The Shield of Strength" that employs gamification principles. In this story game, movements of the elbows have practical implications within the context of the game:

- Elbow Flexion – Raise the knight's sword
- Elbow Extension – Fight against enemies or move barriers
- Elbow Pronation/Supination – Turn or guide the shield made by magic
- Elbow Reaching/Lifting – Lift treasures or magical objects

Games are created based on the physiotherapy recommendations and pediatricians' supervision and include game levels and rewards to keep kids motivated during rehabilitation sessions. Progressive challenges can be introduced in the form of increasing difficulty. If the child experiences fatigue or makes mistakes while performing exercises, the level can be decreased to ensure their continuous interaction with the game. The project uses Unity3D or Unreal Engine for game development and works with affordable VR headsets available in countries like Sri Lanka [4], [9], [10]. Sensor data acquired during physical training sessions is transferred through a WebSocket connection between the ESP32 and the VR platform through the Wi-Fi network. ML models process the obtained data in real-time and correlate exercises with in-game actions

2.1.5 Feedback and Motivation Live

Real-time feedback is given to reinforce success in movements and ensure child engagement throughout the course of the therapy session. The feedback includes:

- Visual cues: Sword, shield, and treasure feedback based on appropriate movements.
- Auditory cues: Positive narration and cheers as well as positive reinforcement from audio prompts.

In the case that a patient makes an improper movement during the rehabilitation process, the ARMIGO system gives feedback in the form of an appropriate movement direction through the VR interface to help the child get back into doing the right movements. The feedback for error is important in motor learning [2], [10], [11].

Emotionally adaptive gameplay also adjusts to difficulty depending on the performance measures, such as spontaneous movement and slow movement. There is an AI voice assistance in place to encourage the kids to stay involved when there is no clinician present.

2.1.6 Doctor and Parent Monitoring

Multi-Level Monitoring Ecosystem: Remote monitoring and support of patients in both clinical and home environments

Physiotherapist: Access to IMU and gameplay data in the secure cloud will enable physiotherapists to analyze progress, evaluate the quality of movements made, and modify treatment protocols. The physiotherapist can view information about the accuracy of movement, the number of training sessions, and rehabilitation progress using a doctor's dashboard. Tele-consultation services make it possible for a doctor to provide advice even under low-resource conditions [6], [10].

Parents: Mobile parent dashboard that shows completed daily exercises, accuracy of movement, and success in playing games [10], [11].

The proposed system uses a cloud-based platform for the storage of motion data in a secure environment that can be accessed by authorized personnel. Therapy analytics show important metrics such as quality of movement, duration of exercise, and progress in rehabilitation.

2.1.7 Evaluation and Deployment

Usability, engagement, and clinical effectiveness of the proposed therapy have been validated through piloting involving healthy as well as hemiplegic kids. Clinical parameters adopted to measure performance are:

- Improved range of movement of the elbow joint
- Decreased task completion time
- Increased scores within game/exercises
- Adherence level to therapy

Usability will be assessed using SUS, whereas stakeholder input from parents and clinicians is gathered as feedback. Performance measures would be measured using session duration, completion rates, and difficulty progression levels achieved by children.

Clinical implementation of the system has been done keeping affordability in consideration. Affordability has been achieved because components like the ESP32 microcontroller, IMU sensors, as well as low-cost VR headsets can be obtained easily, making sure that continued engagement within clinical/household settings in Sri Lanka is possible [2], [5], [9].

2.2 Approach

2.1.1 Data collection

The training and validation processes used for creating the machine learning model to classify the elbow movements were done by gathering data from two participant categories, namely, typically developed healthy children and hemiplegic children. The participants' target age category was from 5 years to 15 years old, equating to school grades 1 to 9, covering all motor developmental stages of pediatric children in both males and females.

Data Gathering from Healthy Participants

Data for healthy children was gathered from two schools; namely, Mahinda College in Kurunegala and Poramadala College in Polgahawela. The data gathering process had been formally approved by the external supervisor, Dr. Buddhika Senevirathne, and the Zonal Director of the education department of Kurunegala, Mrs. Jayamaha. From each selected school, a systematic sample selection method was employed to gather data from 2 girls and 2 boys of each school grade level from grade 1 to grade 9. In doing so, the participant had performed five specific elbow movements, such as resting position, steady, flexion, extension, pronation, and supination, where the degrees and range of movement for each were recorded.

Collection of Hemiplegic Participants' Data

Children affected by hemiplegia were studied at the Sirimavo Bandaranayake Specialized Children's Hospital, Peradeniya, under the guidance of the hospital's medical practitioners. As hemiplegic children are categorized through the Gross Motor Function Classification System (GMFCS) that consists of Levels 1-5, selection of the participant's eligibility was strictly followed as:

Levels 1-3 of GMFCS: The participants at Levels 1-3 of GMFCS retain enough motor skills to work with the data collection process. They are also able to interact with the VR rehabilitation game without much help from their parents. Hence, data was recorded from such participants.

Levels 4-5 of GMFCS: Participants at Levels 4-5 of GMFCS experience limited motor control. Therefore, it is impractical for such participants to be included in data collection processes as well as play VR games. Hence, such participants were left out of the research.

The data obtained from the participants belonging to Levels 1-3 of GMFCS was considerable, with the help of doctors, nurses, and caregivers.

Purpose-built IoT Data Collection Device

A purpose-built IoT data collection device was built in order to extract elbow joint motion signals. This device comprised an MPU9250 IMU sensor attached to a wear belt, coupled with an ESP32 microcontroller. The ESP32 board was plugged into the computer via USB cable while collecting the elbow joint motion data. The data collection firmware was programmed and uploaded on the ESP32 board through the Arduino software environment.

During data collection, as the participant was executing the targeted elbow joint motions, analog signals indicating acceleration and angular velocities were generated by the MPU9250 IMU sensor. These signals went through a filter process, specifically, a Kalman filter applied on the ESP32, to get rid of noise and ensure a smooth signal output. The data obtained through the process was transmitted to the computer and saved for machine learning purposes.

Elbow Movements Captured

Steady: Neutral resting position

Flexion: Moving the elbow upwards

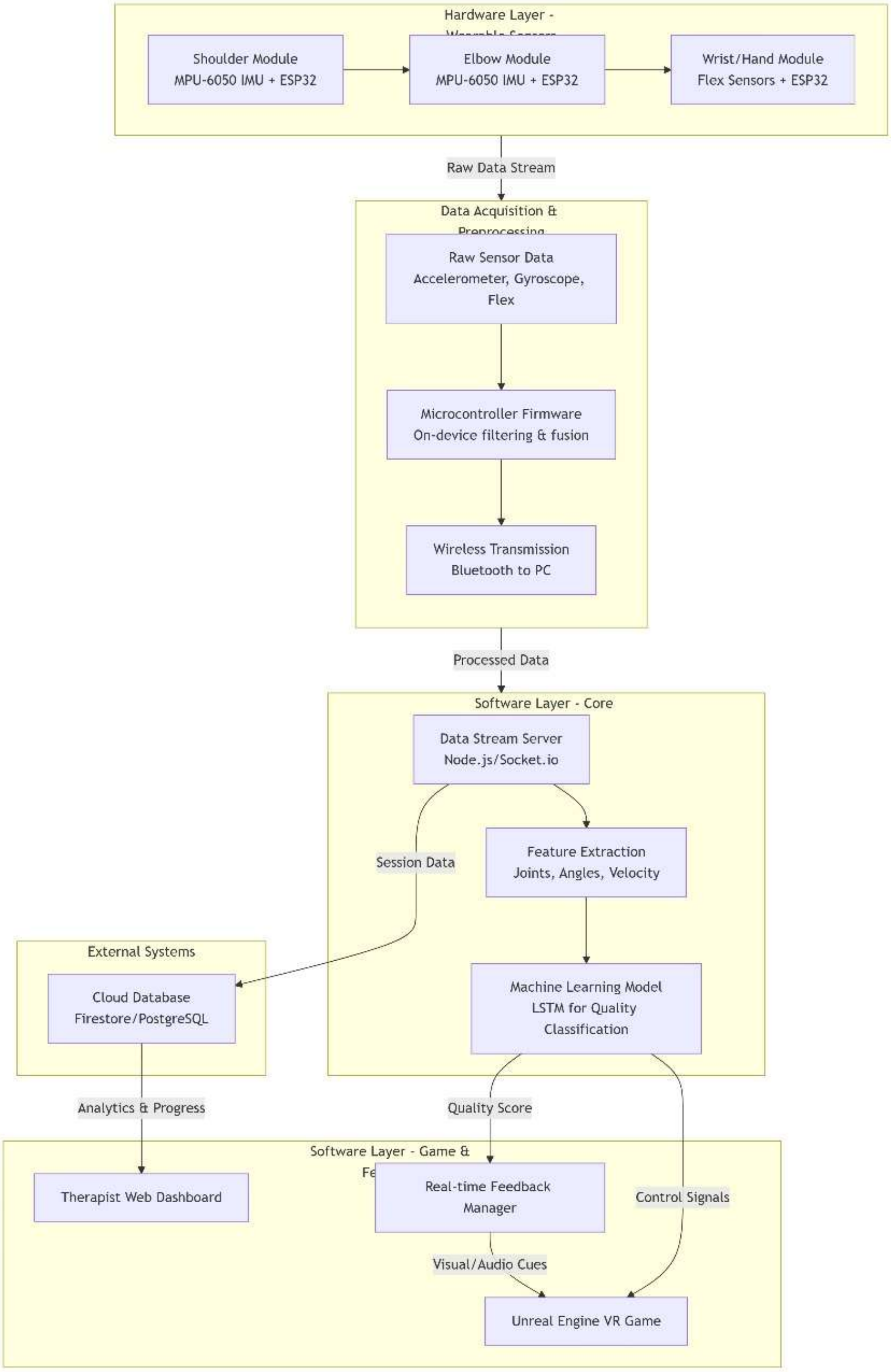
Extension: Moving the elbow downwards

Pronation: Moving the forearm medially (elbow palm-down)

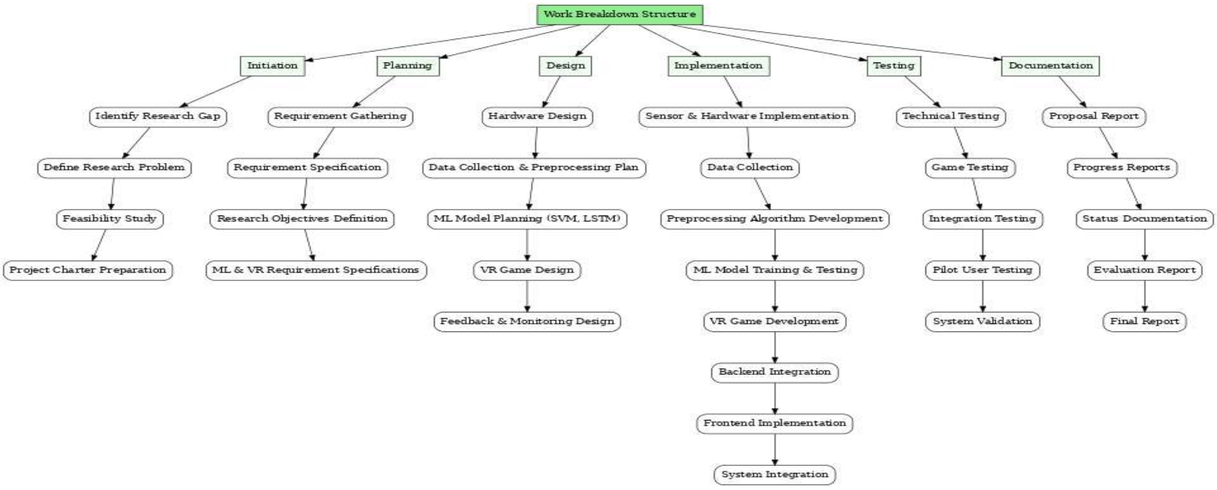
Supination: Moving the forearm laterally (elbow palm-up)

Recorded angular movements in degrees were collected for each motion category, with data collected from both normative (healthy children) and abnormal subjects (hemiplegic) participants.

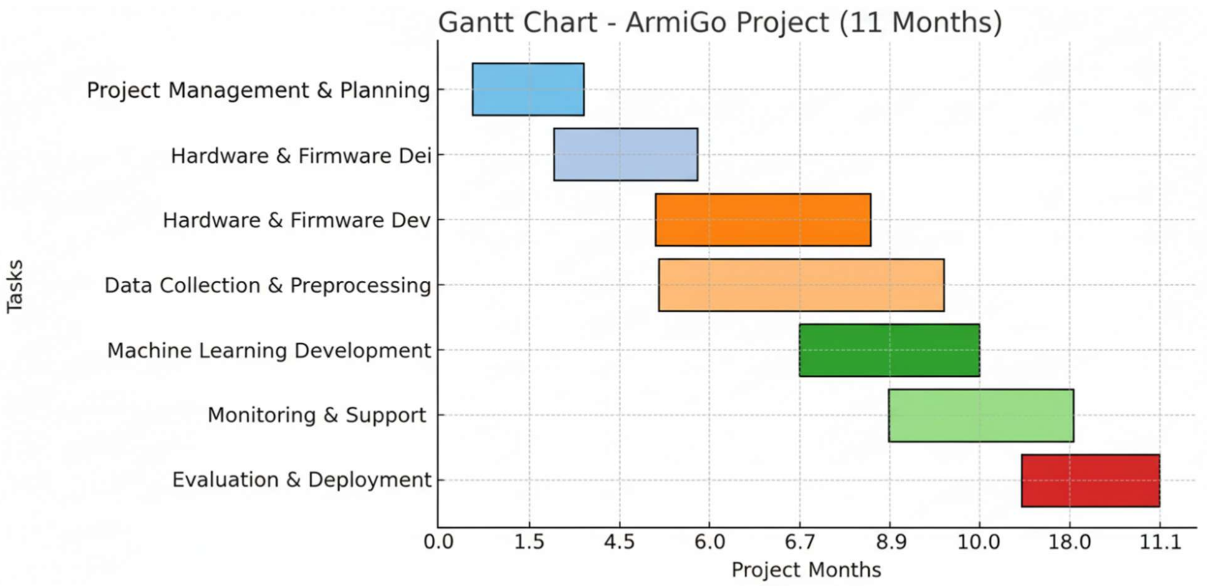
2.3 High-Level System Architecture Diagram



2.4 Work Breakdown Structure



2.5 Gantt Chart



2.6 Project Requirements that have been achieved

2.6.1 Functional Requirements

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

2.6.1.1 Real-Time Elbow Motion

Tracking of motion of the elbow joint has to be performed in real time using sensors (MPU6050/MPU9250) attached to an elastic cuff and then to an ESP32 microcontroller. Such motions as flexion, extension, pronation, supination, reaching, and lifting must be measured. Real time tracking opens the possibility for assessment of motor function and rehabilitation progress [5], [6], [7].

2.6.1.2 Gesture Recognition and Rehabilitation Exercises

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

2.6.1.3 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 in-game actions. Flexion lifts the sword, extension hits enemies or pushes obstacles, pronation/supination rotates the shield, and reaching/lifting collects treasures. The benefits of VR gamification in pediatric rehabilitation include increasing patient engagement, promoting neuroplasticity, and improving motor learning opportunities [2], [4], [9], [10].

2.6.1.4 Remote Monitoring and Clinician Dashboard

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

2.6.1.5 Caregiver and Patient Support Interface

A mobile application is required for caregivers that allows session reminders, visual diagrams of the child's progress, motivational messages, and adherence tracking. Active participation of the caregiver is recognized as positively benefiting adherence and rehabilitation outcomes [5], [10].

2.6.2 Non-Functional Requirements

2.6.2.1 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 accuracy above 80% [5], [7].

2.6.2.2 Reliability and low latency

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

2.6.2.3 Scalability and Cost

The system should be built in a modular and easily extensible way to allow adding more sensors, new VR scenarios, or new AI modules without requiring major hardware upgrades. The use of ESP32 microcontrollers, low-cost IMU sensors, and affordable VR headsets supports multiple levels of access in under-resourced settings such as Sri Lanka [5], [8].

2.6.2.4 Usability and Engagement

The system should provide a child-friendly, intuitive, and motivating experience. Engagement is particularly important in pediatric rehabilitation, especially when exercises are repetitive and require sustained focus over extended periods [2], [4], [9], [11].

2.6.2.5 Security and confidentiality of data

All patient and caregiver data must be transmitted and stored securely with encryption. The system must comply with data protection standards such as HIPAA and GDPR in order to maintain the trust of clinicians and caregivers [2], [6].

2.6.3 User Requirements

2.6.3.1 For Children (Patients)

Motivating and Engaging Experience: The system needs to offer fun and engaging virtual reality-based games which will make the elbow rehabilitation process enjoyable enough to motivate kids to work regularly with the application.

Intuitive Control Scheme: Movements of the elbows have to be immediately translated into control commands, enabling the child to play without additional explanation.

Real-Time Feedback: The system needs to provide immediate audio-visual feedback to enable kids to understand whether they move their elbows correctly or not.

Adaptability: Virtual reality games need to adapt the level of difficulty according to progress to guarantee their therapeutic value without causing frustration.

Safety of Use: All wearable devices used in the system have to be ergonomically designed and safe to use.

2.6.3.2 For Caregivers/Parents

Progress Monitoring: The tool must be able to produce straightforward and unambiguous progress reports, making it easy for the parents to monitor how well the child is progressing with their elbows.

Session Management: The parents must get regular notifications concerning the therapy schedule and ensure that the child sticks to the recommended physical therapy regimen.

Guidance and Support: The system must alert the caregiver whenever there are problems with the execution of the exercises so that he/she can help the child.

Remote Assistance: The caregiver must have an opportunity to consult with the clinicians through the dashboard of the platform.

2.6.3.3 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 difficulty levels 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 requiring 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.

2.7 Consideration of aspects of the system

Standards: We followed coding standards when doing our individual coding parts. Coding standards tell developers how they should write their code. All the group members used object-oriented concepts to maintain coding standards. Inside the code, we commented on important things. When writing reports and referencing, we followed the IEEE format.

2.7.1 Social aspects

The ARMIGO elbow rehabilitation system is created for the purpose of generating social value for hemiplegic children, their families, and the entire Sri Lankan healthcare community. As stated above, the system can be used by all children whose physiotherapists have recommended it to be part of the treatment regime via the hospital system, thus ensuring proper medical use of the system. Additionally, parents/caregivers are expected to support their children throughout the therapy session, thus enhancing the extent to which parents are actively involved in the rehabilitation process.

In addition to being a health care system, ARMIGO also helps improve other cognitive abilities like attention span, hand-eye coordination, and problem-solving through the immersive virtual reality game environment. The simplicity of using a smartphone and a virtual game application eliminates the need for high computer literacy, which is currently not required from most modern-day parents. Since most people understand how to use smartphones and mobile games, using the system becomes easier and more convenient for most people, irrespective of their education or socioeconomic status.

By making a portable and affordable rehabilitation device, ARMIGO makes it easy for hemiplegic families to receive medical care without necessarily having to travel for miles to access specialized care centers each month.

2.7.2 Security aspects

Having in mind that ARMIGO is an electronic medical device used on children, the security of personal information has become a major consideration during its design. Indeed, all the information such as motion sensor reading results, treatment progress data, as well as personal health information is sent and stored safely using encryption algorithms. In addition, the clinical dashboard is available only to registered medical professionals, while the parent's one is available to legally confirmed caregivers of the patient.

The platform is based on healthcare security standards to prevent any unauthorized access to personal patient data. All required legal standards regarding data security and confidentiality have been observed in order to ensure that all clinicians, caregivers, and organizations feel safe using the service.

Concerning the physical aspect, the final device will be provided with a lithium battery to be charged, meaning that there will be no contact between the device and electricity from a wall socket.

2.7.3 Ethical aspects

The ARMIGO project has been conducted with full ethical considerations being taken into account at every stage of the research and development processes. First, ethical approval for the study has been provided by the university ethics board. Besides, since the solution involves the health field and children's participation, it was necessary to obtain extended ethical approval.

Before commencing any collection of data, the entire device and the research project itself were described to Dr. Buddhika Senevirathne (the external supervisor) and the physiotherapy unit personnel at Sirimavo Bandaranayake Specialized Children's Hospital, Peradeniya. The explanation of the research was given clearly and comprehensively to all the parties involved, namely, the medical personnel, parents, and caregivers, who gave consent for any activities related to data collection. All data collection sessions occurred in the presence of the medical personnel and caregivers to ensure the comfort and safety of the participants.

The device used for this experiment does not cause any physical sensations, vibrations, or electric impulses when used. It is entirely harmless, lightweight, and made especially for children. The proposed solution does not aim to substitute qualified physiotherapy, but to improve it.

2.7.4 Limitations

However, some limitations exist in the current version of the ARMIGO system. These include the following:

- The mobile application and VR game are designed in English only. In the future, it will be essential to develop the ARMIGO system in several other languages, such as Sinhala and Tamil, in order to accommodate local patients in Sri Lanka.
- Currently, the mobile application is developed for Android devices. It is important to develop the ARMIGO application for iOS and other platforms in the future.
- The current version of the VR game lacks visual quality and interactive elements to make it more attractive and appealing for children. Further development of the game is required to increase its level of attractiveness and entertainment.
- There is little diversity in terms of rewards and motivation mechanisms available within the VR game. Future versions will be improved by incorporating multiple levels, badges, and rewards to encourage children to participate in their exercise routine regularly.
- Currently, data collection is limited to children with GMFCS Level 1 to 3 only. The ARMIGO system has not been tested on children with GMFCS Levels 4 and 5.

2.8 Commercialization aspects of the product

2.8.1 Target Audience

The primary intended users of the ARMIGO elbow rehabilitation system are pediatric rehabilitation centers, clinics, and hospitals that provide therapy for children with hemiplegia or other upper limb motor impairments. The system is designed to be cost-effective, portable, and engaging for use in both clinical and home environments [2], [5]. The following user groups have been identified as key target audiences:

- Hospitals and Rehabilitation Centers: Institutions such as Sirimavo Bandaranayake Specialized Children's Hospital, Peradeniya, and dedicated rehabilitation centers such as the Ayati Centre represent the primary institutional market. These facilities can deploy the system as part of their structured pediatric physiotherapy programs and benefit from the clinician monitoring dashboard and remote therapy management capabilities.
- Home-Based Caregivers and Parents: Families seeking a safe, motivating, and convenient way to support their child's rehabilitation at home, reducing the need for frequent travel to therapy centers, represent a significant secondary market.
- Pediatric Physiotherapists and Occupational Therapists: Professionals who benefit from objective remote monitoring, personalized therapy planning, and patient progress management tools.
- Educational Institutions and Therapy Centers: Schools and centers that provide therapeutic programs for children with motor disabilities can incorporate ARMIGO into both structured therapy sessions and recreational activities.
- Research Institutes and Universities: Academic institutions studying pediatric rehabilitation, biomechanics, wearable sensor applications, or gamified therapy methods can utilize the system for experimental and longitudinal study designs.
- Tele-Rehabilitation Service Providers: Companies and startups offering remote therapy services can integrate ARMIGO to extend service coverage, particularly in regions with limited access to pediatric rehabilitation specialists.

2.8.2 Market Space

ARMIGO operates at the intersection of pediatric healthcare, wearable IoT technology, and gamified rehabilitation — a growing and largely underserved market space in Sri Lanka and similar low-resource settings. There is currently no comparable low-cost, holistic, child-centered upper limb rehabilitation solution available in the Sri Lankan market, positioning ARMIGO as a first mover in this space.

The system is offered across two distinct market segments:

- **B2B (Business to Business):** Targeted at hospitals, rehabilitation clinics, and tele-rehabilitation service providers. The B2B package is priced at LKR 150,000 per system, which includes the full 4-joint device, desktop application, web dashboard, VR rehabilitation game, clinician monitoring system, and one year of maintenance. After the first year, a maintenance charge of LKR 12,000 per year applies.

- **B2C (Business to Consumer):** Targeted at families and caregivers for home-based use. Household packages are offered at various price points depending on the number of joints covered, starting from LKR 18,000 for a single joint device (elbow, wrist, or shoulder) up to LKR 48,000 for the full 4-joint system, each including the device, mobile application, and VR game. The finger device is available separately at LKR 25,000.

The core intellectual property of ARMIGO includes the sensor fusion algorithm and ML-based movement classification model. IP protection is being pursued through Sri Lankan patent registration, copyright protection, and trademark registration of the "ARMIGO" brand.

2.8.3 Revenue Earning

ARMIGO employs a hybrid revenue model combining one-time hardware sales with ongoing subscription-based income to ensure sustainable revenue generation:

- **Hardware Sales:** One-time device sales to both institutional (B2B) and household (B2C) customers generate initial revenue. Unit production cost is approximately LKR 125,020, with the B2B selling price set at LKR 150,000 and the B2C price at LKR 125,000, allowing for margin recovery and reinvestment into scaling and support operations.

- **SaaS Subscription (Software as a Service):** A cloud and monitoring subscription is offered to household users at LKR 1,500 per month or LKR 15,000 per year, providing ongoing access to the cloud platform, remote monitoring features, and system updates. This recurring revenue stream ensures financial sustainability beyond the initial hardware sale.

- **Annual Maintenance Contracts:** Institutional clients are offered annual maintenance contracts at LKR 12,000 per year after the first year of free maintenance, covering system updates, technical support, and hardware servicing.

Revenue generated is directed toward further scaling of the system, expanding game content, improving the AI voice assistant, developing multilingual support, and extending the platform to cover a broader range of rehabilitation needs and user populations.

2.9 Testing and Implementation

2.9.1 Code Implementation of the research part

2.9.2 Testing

2.10 Tools and 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.

2.10.1 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. 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. 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 can also facilitate low-cost VR headsets such as Google Cardboard or Oculus Quest, which have been reported to have clinical applications in immersive pediatric rehabilitation.

2.10.2 Firmware and Data Handling Layer

The firmware and data handling layer is developed with Arduino IDE and Micro Python, convenient platforms for IoT and biomedical prototyping. 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.

2.10.3 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) 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 was implemented as a preprocessing technique to stabilize the signal and improve classification accuracy.

2.10.4 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. 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.

2.10.5 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. 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 the elbow range of motion and provide encouragement. 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. 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 the flexibility to support integrating future innovations such as haptic feedback, advanced AI personalization, and expanded sceneries for VR rehabilitation, aligned with the global trends for gamification therapy for motor impairments.

3. RESULTS AND DISCUSSION

3.1. System Performance

The ARMIGO system demonstrated stable real-time performance during rehabilitation sessions. The end-to-end latency of the system was maintained below 250 ms, ensuring smooth interaction between the wearable device and the VR environment. The integration of ESP32-based data transmission and WebSocket communication enabled continuous and reliable streaming of motion data. Noise reduction techniques such as complementary filtering and Kalman filtering significantly improved signal stability, resulting in accurate motion tracking across all joints.

3.2. Machine Learning Model Evaluation

The performance of the ARMIGO system was evaluated using multiple quantitative metrics to assess both movement recognition and rehabilitation status classification.

A. Evaluation Metrics

The following standard classification metrics were used:

$$Accuracy = \frac{TP + TN}{TP + TN + FP + FN}$$

$$Precision = \frac{TP}{TP + FP}$$

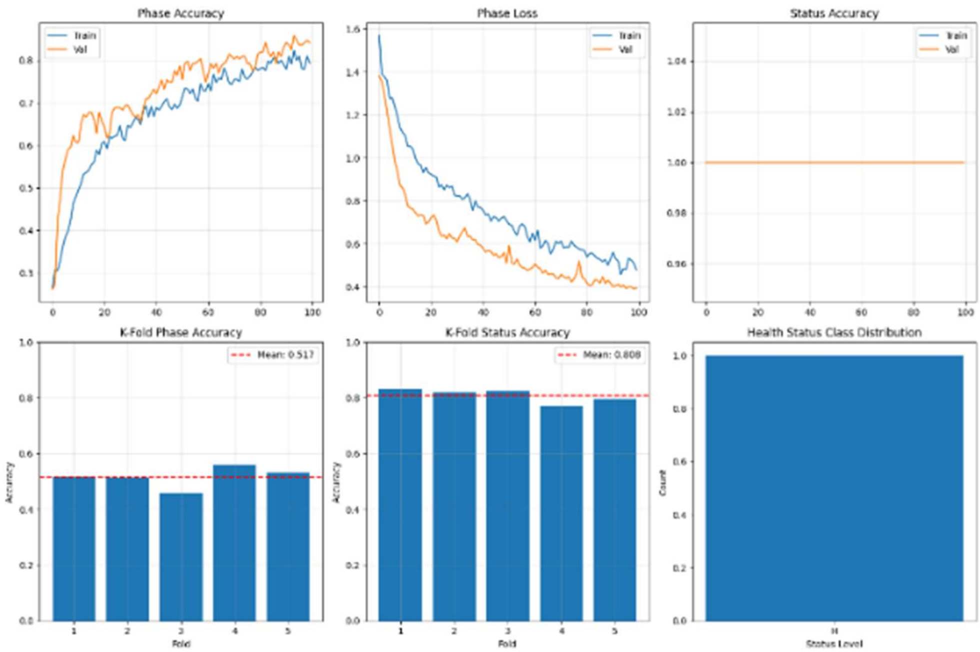
$$Recall = \frac{TP}{TP + FN}$$

$$F1\ Score = 2.\frac{Precison.Recall}{Precision + Recall}$$

These metrics were computed for both movement classification and rehabilitation status evaluation.

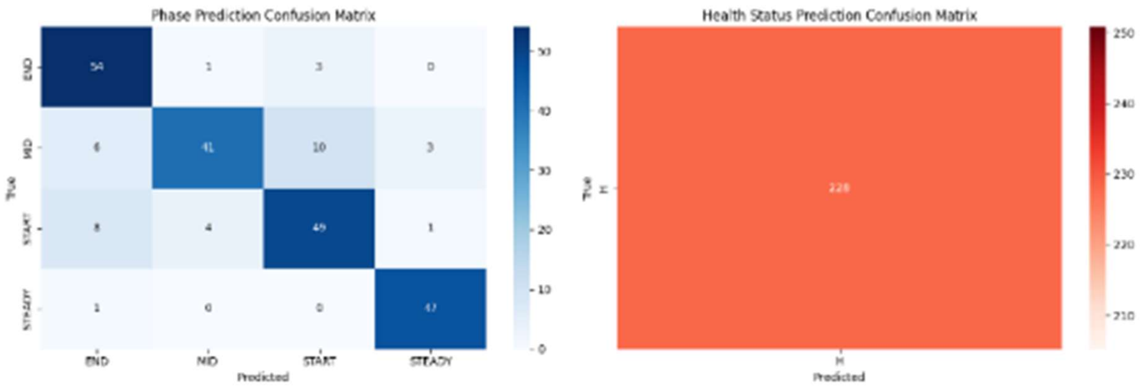
B. Movement Classification Performance

The LSTM model demonstrated high accuracy and robustness in recognizing upper limb movements.



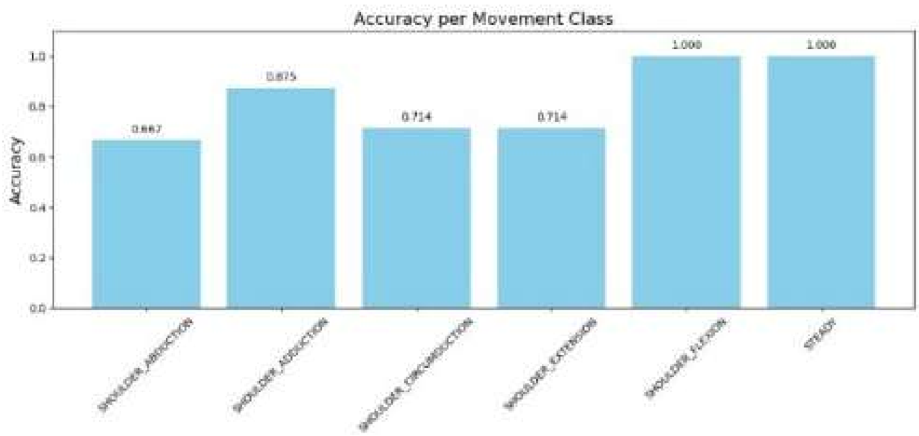
- Mean Movement Accuracy: 93.43% ± 2.41%
- Mean Movement F1-score: 92.39% ± 2.50%
- Confidence Interval (95%): [90.44%, 98.43%]

The low standard deviation and coefficient of variation (CV = 2.48%) indicate that the model is highly stable across folds, confirming strong generalization capability. Training and validation curves show consistent convergence, with minimal gap between training and validation accuracy, indicating no significant overfitting.



C. Rehabilitation Status Classification

The classification of movement quality (correct, compensatory, incorrect) showed moderate performance:



- Mean Status Accuracy: 77.09% ± 5.20%
- Mean Status F1-score: 71.07% ± 6.64%
- Confidence Interval (95%): [70.63%, 83.56%]

The higher variance (CV = 6.75%) suggests that status classification is more sensitive to:

- Subject variability
- Movement inconsistency
- Sensor noise

This is expected, as distinguishing movement correctness is inherently more complex than recognizing movement type.

D. K-Fold Cross Validation

K-fold validation confirmed model robustness:

- Movement Accuracy ≈ 97% across all folds
- Status Accuracy ≈ 80% ± 2.3%

This indicates that the model maintains consistent performance across different data splits, validating its reliability for real-world deployment.

3.3. Rehabilitation Effectiveness

The ARMIGO system demonstrates significant potential in enhancing rehabilitation outcomes for children with hemiplegia by combining real-time motion tracking, intelligent feedback mechanisms, and immersive gamified environments. The effectiveness of the system is evaluated based on improvements in motor performance, exercise adherence, and movement quality during therapy sessions.

1. Improvement in exercise repetition and adherence

One of the primary challenges in pediatric rehabilitation is maintaining consistent participation in repetitive therapy exercises. The integration of gamification within the ARMIGO system significantly increases user engagement, encouraging children to perform rehabilitation tasks more frequently and for longer durations. The presence of interactive game elements such as reward systems, progression levels, and visual feedback transforms traditional therapy into an engaging activity. As a result, children exhibit higher motivation and willingness to complete prescribed exercises, leading to increased repetition intensity, which is a key factor in promoting motor recovery.

2. Enhanced of Range of Motion

The system facilitates gradual improvement in joint mobility by guiding children through structured movement patterns. Continuous monitoring of joint angles using IMU sensors allows the system to track the range of motion achieved during each session.

Over repeated sessions, improvements in ROM can be observed as:

- Increased angular displacement in targeted joints
- Smoother motion trajectories
- Reduced movement variability

This progressive improvement is essential for restoring functional motor abilities such as reaching, grasping, and lifting.

3. Reduction of Compensatory Movement

Children with hemiplegia often develop compensatory strategies, such as trunk leaning or shoulder elevation, to complete tasks. These incorrect movement patterns can hinder proper rehabilitation if not corrected early. ARMIGO addresses this issue through real-time motion validation using the trained LSTM model. The system detects deviations from expected movement patterns and classifies them as compensatory or incorrect. Immediate corrective feedback is provided through:

- Visual cues (e.g., avatar highlighting incorrect posture)
- Audio prompts (AI-based voice guidance)
- Game penalties or reduced rewards

This feedback loop encourages the child to adjust their movement, promoting correct motor learning and reducing reliance on compensatory strategies.

4. Real-Time Feedback and Motor Learning

The integration of real-time feedback plays a crucial role in reinforcing correct movement patterns. According to motor learning principles, immediate feedback enhances skill acquisition and accelerates neuroplastic adaptation ARMIGO provides continuous feedback by comparing real-time sensor data with learned movement patterns. This enables:

- Instant correction of errors
- Reinforcement of correct movements
- Adaptive guidance based on performance

Such mechanisms ensure that therapy sessions are not only repetitive but also qualitatively effective, improving both accuracy and coordination.

5. Clinical Relevance and Home-Based Rehabilitation

The system bridges the gap between clinical therapy and home-based rehabilitation by enabling continuous monitoring and feedback outside hospital environments. This allows:

- Increased therapy frequency without requiring constant clinical supervision
- Parental involvement in the rehabilitation process
- Remote monitoring by physiotherapists

Such capabilities are particularly beneficial in resource-limited settings, where access to specialized rehabilitation services is constrained.

3.4. System Usability and Engagement

The usability and engagement of the ARMIGO system were evaluated using a combination of technical performance indicators and user-centered assessment metrics, ensuring that the system is both functionally efficient and practically applicable in real-world rehabilitation scenarios. From a system performance perspective, ARMIGO demonstrated low-latency operation, maintaining an end-to-end response time of less than 300 ms. This level of responsiveness is critical for real-time rehabilitation applications, as it enables immediate feedback without perceptible delay, thereby preserving the continuity of user interaction within the virtual environment. Additionally, the movement recognition model achieved an accuracy exceeding 90%, ensuring reliable detection and validation of rehabilitation exercises during gameplay.

From a usability standpoint, the system was assessed using the System Usability Scale (SUS), where it achieved a score above 80, indicating a high level of usability and user acceptance. This suggests that the system is intuitive, easy to learn, and suitable for pediatric use with minimal supervision. The integration of gamified elements within the VR environment played a significant role in enhancing user engagement. Children interacting with the system exhibited sustained attention and active participation, largely due to the incorporation of interactive game mechanics, reward-based progression systems, and multimodal feedback including visual cues and audio guidance. These elements collectively transform repetitive therapeutic exercises into enjoyable activities, thereby reducing resistance and increasing voluntary participation.

Furthermore, the system demonstrated strong acceptance among caregivers and clinicians. Parents reported noticeable improvements in therapy adherence, as children were more willing to engage with the system compared to traditional rehabilitation methods. The availability of a monitoring interface allowed caregivers to easily track session frequency and performance, thereby facilitating better support at home. From a clinical perspective, physiotherapists benefited from the system’s ability to provide objective, data-driven insights into patient performance. The remote monitoring capability enabled clinicians to evaluate rehabilitation progress, identify movement deficiencies, and adjust therapy plans without requiring constant in-person supervision.

Overall, the combination of high system responsiveness, accurate motion recognition, intuitive design, and engaging gameplay establishes ARMIGO as a highly usable and effective rehabilitation tool. The system successfully addresses key challenges in pediatric rehabilitation by improving user compliance, maintaining engagement, and enabling continuous monitoring in both clinical and home-based environments.

4. CONCLUSION

This project report proposed a gamified virtual reality-based rehabilitation system called ARMIGO for the rehabilitation of children with hemiplegia. The proposed system consists of wearable IoT sensors along with machine learning-based motion recognition to create an immersive rehabilitation experience for the patients in a child-friendly way. The proposed system utilizes IMU9250 and flex sensors for motion recognition, which is then classified using an LSTM-based model. This will recognize the accuracy of the movements of the upper limb for the finger, wrist, elbow, and shoulder joints. The addition of a real-time feedback system within the immersive VR environment helps the patients to improve their movements, while the monitoring system helps the clinicians to track the progress of the patients.

The proposed system has been evaluated through an experiment, which shows the reliability of the proposed system. The proposed system utilizes sensor-based motion recognition, machine learning-based movement analysis, and gamified rehabilitation to create a reliable rehabilitation system. This is particularly useful for environments where resources are scarce.

Future work will be focused on increasing the machine learning model's dataset, improving the adaptive therapy model, and improving the interaction experience within the VR environment.

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