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

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DECLARATION OF THE CANDIDATE AND SUPERVISOR

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ABSTRACT

Hemiplegia in children with perinatal stroke, traumatic brain injury, or cerebral palsy results in significant impairment of upper limb function and fine motor skills. Trouble with grasping, pinching, extending, releasing, and coordinated tapping directly, which limit independence in daily activities and impact aspects of a child's social or emotional well-being. Traditional rehabilitation offers standardized guided therapeutic exercises, which include a good amount of success, but it can be seriously limited in places with low resource settings such as Sri Lanka for many reasons, including the limiting-scale of available therapists, affordability, distance traveled to therapy, and client compliance due to repetitive nature of basic therapeutic exercises. This proposal introduces a low-cost and technology-driven rehabilitation platform that combines wearable flex-sensor gloves, machine learning (LSTM), and a gamified virtual reality (VR) environment. The platform captures all of the children's finger muscles in real-time with flexsensor gloves, with those movements classified into six functional categories, then associated with prescribed therapeutic movement during the narrative of a VR game entitled, "Magic Quest: The Enchanted Fingers". As children participate in the magical adventure, they perform prescribed therapeutic exercises to cast spells, open runes, and unlock enchanted treasures Rehabilitation will never be so much fun and motivating A multi-tiered support ecosystem expands the potential of the platform. Clinicians can monitor a child progress, prescribing modifications and providing feedback at any moment; parents can monitor therapy adherence and outcomes using the caregiver dashboard; and an AI voice assistant will provide consistent encouragement when clinical monitoring cannot be applied. The system sustains engagement with adaptive difficulty scaling, real time feedback, audiovisual and visual representations. By transforming the traditional model of clinical rehabilitation into gamified immersive therapy with the technology of remote media, it captures key barriers that limit care in pediatric hemiplegia, accessibility, motivation and continuity of care. The technology has the potential to improve a child's motor recovery therapy adherence and emotional well-being in a scalable way in low resource health care settings.

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

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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, Fingers strength and function are a particularly important impairment for reducing independence. The Fingers 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 finger motions 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 Flex/IMU-based sensing and ML-driven movement classification into a VR game called "Magic Quest: The Shield of Strength". In this game, children assume the role of a young magician tasked with restoring peace to a medieval kingdom. Each therapeutic finger movement corresponds to a meaningful in-game action:

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 finger 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 Flex/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

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

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

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

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

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

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

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

1.1.1 Clinical context and rehabilitation requirements

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

1.1.2 Virtual reality (VR) and serious games as rehabilitation

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

1.1.3 Wearable sensing technologies for finger rehabilitation

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

1.1.4 Machine learning for gesture classification

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

1.1.5 Motivation and Engagement in Pediatric Rehabilitation

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

1.1.6 Doctor, parent, and AI-assisted monitoring

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

1.2 Research Gap

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

[7]. The engagement in therapy including motivation, adherence, and, engagement are emphasized in children with the use of gamification with VR compared to traditional therapy [8].

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

Another gap is that most available sensor-based rehabilitation systems do not provide real-time corrective feedback. The available systems record kinematic data for analysis after therapy, but it is rare that they incorporate this data into real-time guidance to the child, within the VR gameplay. This current gap limits the potential for motor learning as real-time feedback can greatly enhance neuroplasticity. In addition, most of the above studies have developed and subsequently validated their systems with adult stroke survivors as their target population [7] and have not focused specifically on the pediatric population. Children with hemiplegia have specific developmental, motivational, and engaging needs that will not be found with adult rehabilitation, so repurposing a platform designed for adults will not effectively meet these needs. In the Sri Lankan context, these realities are complicated further by systemic barriers which include a shortage of pediatric therapists, expensive therapy sessions, rehabilitation centers being scarce in the rural areas and non-adherence to home-based therapy due to boredom and a lack of supervision and motivation [2]. Thus, the research gap identified is the lack of a low-cost, integrated VR rehabilitation system for finger rehabilitation in children with hemiplegia in Sri Lanka. A system must combine wearable flex-sensor technology, gesture recognition by ML, immersive VR gaming and caregiver/clinician support to develop a child-centered integrated platform that provides therapy and maintains motivation/access outside of highly specialized clinical environments.

1.3 Research Problem

While advances in pediatric neurorehabilitation are significant, the lack of a comprehensive, technology-driven framework to fully address the many factors affecting upper limb motor recovery among children with hemiplegia remains problematic. Current literature (see this survey) illustrates that rehabilitation solutions targeting components of motor recovery are available; however, these solutions are fragmented and do not integrate clinical oversight, family involvement, and intelligent, adaptive assistance into one comprehensive system.

1. **Insufficient Personalization in Existing Game-Based Rehabilitation Systems**

   Recent rehabilitation approaches employing orthosis for children with hemiplegia have principally used standard physiotherapy practices, whereby game-based rehabilitation is considered supplementary and generic, rather than a dynamic, individualised, adaptable strategy. Furthermore, each child's neurological profile, motor recovery progress speedy ability and functional ability demonstrate how game-based rehabilitation is calibrated to each child in contemporary rehabilitation. In addition, the one-size-fits-all strategy of contemporary rehabilitation fails to take full advantage of game-based rehabilitation providing a precise means of restoring motor skills, resulting in less than optimal outcomes for a group of children with many different recovery paths.

2. **Absence of Real-Time Clinical Monitoring and Adaptive Treatment Pathways**

   A key issue with many of the current rehabilitation games is they typically operate separately from qualified health care practitioners in a live environment. Health care providers do not obtain accurate performance data at the level of each session because real-time performance-monitoring systems are not in place. This disconnect results in a significant delay in treatment modification for the child, as the child continues to experience the complications of using an inappropriate and/or ineffective program until the next regularly scheduled review prompts the modification of the program. Therefore, a robust framework must be in place to provide continuous, clinician-accessible performance dashboards, which enable clinicians to dynamically adjust therapeutic goals, difficulty levels, and session lengths in response to the changing functional abilities of the child.

3. **Marginal Parental Involvement Despite Their Central Therapeutic Role**
   The literature on rehabilitation continues to demonstrate that parental/caregiver involvement is one of the most important predictors of long-term success of motor recovery within pediatrics. However, most of the available rehabilitation platforms provide little, if any, opportunity for parents to participate beyond as passive observers. The dearth of systematic opportunity for parents to participate as active agents of rehabilitation has resulted in a serious underutilization of their specialized ability to support ongoing, supervised practice at home, provide emotion-based pre-motivational support in context, and offer support for therapy objectives between sessions. For a next-generation rehabilitation framework, this will require intentionally developing structured pathways for parents to participate, as well as providing caregivers with understandable feedback about their child's progress and appropriate tools to guide and prompt their own behaviors in order to transform them from passive observers into empowered co-therapists throughout their child's recovery process.

4. **Lack of AI-Driven Voice Assistance for Continuous Guided Engagement**
   Currently, there is no rehabilitation system reviewed in this literature survey that uses intelligent, context-sensitive voice assistance for therapy and motivation as the primary mode of providing therapy and motivational reinforcement. This is a huge gap in rehabilitation, especially when so much of a child’s rehab process occurs without being seen by a healthcare professional. An AI-based voice assistant, which could provide real-time encouragement, corrective instruction and emotional support, could create an ongoing therapeutic presence that could assist with bridging the motivational and guidance gap that exists between formal therapy sessions. This would be very beneficial for children with

hemiplegia who rely on verbal interaction to be able to communicate effectively and to maintain motivation during repetitive motor activities through the provision of positive reinforcement on an ongoing basis

5. **Inadequate Granularity in Finger-Level Motion Monitoring for Fine Motor Rehabilitation**

   Although a number of current systems perform adequately in tracking larger gross movements of upper limbs, such as flexion/extension of elbow, they are severely limited in their ability to detect small individual movements of fingers; and small, multi-joint kinematic motion is critical to restoring fine motor capability and dexterity of the hands for children with hemiplegia. For children with hemiplegia, finger individuation, ability to modulate grip force, and fine motor coordination are often completely absent, meaning they have difficulty completing the basic tasks necessary to lead active, productive lives involving both academic and social interaction. Rehabilitation systems lacking sensor-platforms and analytical frameworks with the ability to detect motion for all the joints of the fingers cannot provide the basis on which to identify small improvements in functional abilities (e.g., independent finger function), determine movement compensations, and provide the biofeedback necessary to facilitate fine motor recovery. To bridge this gap requires the integration of high-resolution motion capture and biomechanical analyses that provide kinematic data throughout the gross movements associated with the wrist and elbow and the entire movement complexity of the hemiplegic hand.

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 Flex and IMU sensors and machine learning for enabling and tracking rehabilitative finger based exercises for young hemiplegic patients, and supporting efficient home therapy with clinical monitoring from a distance.

1.4.2 Specific objectives

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

An end-to-end engineering process has been taken to create a smart, wearably therapeutic glove system for capturing real-time, high-fidelity data on the movement of your fingers. This design includes a small, embedded electronics packaging using flex sensors for measuring the amount of flexing and extending your fingers at their joints. The gloves are equped with five clinical therapeutic exercises that can be performed at each finger joint or for your hand as a whole - these are flexion, extension, abduction, adduction, and circumduction.

The embedded electronics use an ESP32 microcontroller that acts as the main processor for processing collected motion data and applying various forms of conditioning to ensure the data is as accurate as possible. For example, each motion sensor produces an output based on the position of your joints and the amount of motion of your fingers from that joint (an "angular distance"). Therefore, the condition process will allow for many adjustments to be made to account for children having varying sizes and shapes.

Once the conditioning process has been completed, the mechanical data will be transferred via Bluetooth or a WebSocket protocol to a connected PC or VR system. By establishing a low-latency data pipeline between the glove and the computer or VR system, physiotherapists can obtain and analyze data at their leisure. In order to achieve comfort while wearing the glove during extended periods of time, the gloves were also designed ergonomically for children with limited or no motion available at their hemiplegic extremities.

This project developed and optimized an LSTM-based deep learning model for accurately recognizing therapeutic finger movement sequences. LSTM networks were uniquely suited to this application, due to their ability to model temporal relationships among sequential sensor data; this was especially important given that therapeutic exercises— flexion, extension, abduction, adduction, and circumduction—are time-based movements but have unique temporal signatures rather than distinct locations. A labeled dataset was collected from children with hemiplegia and typically developing children, systematically encompassing the entire range of movement quality, speed, range, and compensatory patterns across these two groups. The model was trained, validated, and tested on a minimum of 90% classification accuracy, using dropout regularization and early stopping strategies to avoid overfitting on the limited pediatric clinical dataset during training. The model was then deployed as an embedded inference module in the system pipeline and received live sensor streaming data and produced movement classification results in real time to drive downstream reinforcement feedback and gaming dynamics.

The design of the immersive Virtual Reality (VR) game was to have five therapeutic exercises incorporated in the use of engaging narrative gaming to ensure that motivation remains high throughout repeated rehabilitation sessions. The VR game, Magic Quest: The Enchanted Fingers (Magic Quest), was specifically developed in Unity to incorporate the prescribed five therapeutic exercises through an engaging magical storyline appropriate for a child. For example, instead of simply flexing (the finger) during a therapeutic exercise, the child would be closing a magical fist around a glowing orb; instead of merely extending (the finger) during a therapeutic exercise, the child… (example: uses finger extension to spread the energy of power over an enchanted surface); etc.

In addition, the VR game world, characters, and storyline had a high degree of collaborative development with occupational therapists throughout the development phase. As a result, every game action within the game-supportive mechanics were grounded in and aligned with existing therapeutic exercise protocols associated with rehabilitating a hemiplegic (child) upper extremity. Furthermore, the level of difficulty in Magic Quest increased through the use of an adaptive scale (created and embedded within the game's meta-layer) that automatically adjusts the complexity of movement in relation to the range of motion requirements and the repetitions required based on the child's previous performance. Thus, the child would always work within the optimal challenge zone for motor learning while avoiding undue frustration and/or fatigue.

The multi-modal real-time feedback system that was developed and implemented to assist with guiding, correcting, and motivating children while performing accurate therapeutic finger movements during gameplay received its real-time movement classification data from the LSTM model and converted that data into a response in an immediate, therapeutic way across three channels (Visual, Auditory, Gamified) so that each child on a continuous basis would have access to actionable feedback about the quality and accuracy of his/her finger movement with respect to therapeutic execution criteria throughout each therapy session.

During VR sessions, the dynamic movement of the child's virtual hand avatar provided immediate visual indications of movement accuracy and, when the child performed a therapeutic exercise correctly, visual feedback included glowing highlights, particle effect animations, and successful objective animations in the game. The auditory soundscape was used for the purpose of providing positive reinforcement for performing developmental movements correctly (using magical tones, achievement sound cues, and narrative voice). In addition, near-correct movements were provided with gentle auditory sound cues without interrupting immersion, or discouraging the child from continuing with their game play. In addition, there were direct, exclusive links between the progression of individual scores, experience points, magical achievements, and milestones within the narrative plot of the game, and the overall accuracy, completeness, and quality of the therapeutic finger movements performed by each child as classified by the LSTM model; therefore, the reward structure was designed to provide the intrinsic motivation for performing therapeutic finger movements correctly and converting every positively executed therapeutic exercise into an actual step towards progressing the storyline of the game.
We conducted pilot tests on the system's technical performance, usability and therapeutic engagement using children with hemiplegia in Sri Lanka. We evaluated the accuracy, consistency and calibration of the sensor pipeline for each participant, taking into account their hand sizes and levels of spasticity, as well as the LSTM model's performance in deployment conditions relative to classification accuracy, sensitivity, specificity and confusion matrix analysis of the five movement categories. Usability was assessed using standard System Usability Scale (SUS) surveys administered to therapists and parents, along with structured qualitative interviews and observational assessments of child participants in terms of ease of wear, comfort during extended use, clarity of feedback mechanisms and accessibility of monitoring interfaces. Therapeutic engagement was measured by using objective behavioral indicators, including total game play time

during the session, rates of voluntary repetition, adherence to sessions throughout the pilot study and observed emotional and motivational responses while playing, as well as therapist-reported clinical impressions and observations by parents to provide a comprehensive, multi-perspective evaluation of the system's therapeutic value in real-world settings.

2. METHODOLOGY

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

2.1 Understanding the key pillars of the research domain

2.1.1 Sensor selection and hardware design

The rehabilitation glove that was designed for the system has been developed as a wearable device which is able to accurately and reliably monitor small movements of the fingers. In total there are five sensors located in a soft child-friendly glove; one sensor for each finger. Each of the sensors is located on the back side of the finger, so that it is able to measure the amount of bending of each of the finger segments and provide data concerning the amount of angular movement created when a finger bends during therapy sessions. Flex sensors were chosen for this project due to their low cost, light weight, high degree of responsiveness to changes in angular position, and their documented success rate for use in upper limb rehabilitation systems; therefore making them appropriate for use in the rehabilitation process with children.

As each of the flex sensors is bent at a particular angle, the resistance of that sensor will change in a direct correlation to the amount of angle the sensor has been bent; the relationship can be expressed as:

$$R(\theta)=R0+k\theta$$

$R(\theta)$ refers to the amount of resistance seen by a sensor when it is bent at a given angle. R_0 is defined as the sensor's baseline resistance when it is flat (unbent). k is known as the sensor sensitivity coefficient; θ is measured as the measure of an angular displacement in degrees.

To convert each flex sensor's variable resistance output into a value measurable as an electrical signal, the output voltage of each flex sensor's corresponding voltage divider circuit can be calculated using the following equation which produces a low current output voltage as the flex sensor's input, leading to a higher output voltage:

$$V_{out=}V_{in}\times\frac{Rf}{R(\theta)+Rf}$$

The ADC in the ESP32 will read the Analog voltage output and create a raw Digital output, which has values that are proportional to its corresponding voltage and fall within the range of 0 - 4095 (12 bit resolution). We chose to use the ESP32 Microcontroller as the CPU of the glove system due to its size, power consumption, processing power, and built-in WiFi/Bluetooth, making it an extremely effective method for wirelessly communicating to the VR platform. The Microcontroller will poll all five of the sensor channels, process the raw ADC values and transmit the processed data stream to a Unity based Virtual Reality (VR) environment via WebSocket.

In order to provide every child with an accurate and personalized measurement of Degrees of Angular Displacement for their individual children, we performed a two-step calibration process to calibrate their sensors. The first step was Static Calibration, in which we asked each child to hold their hand fully extended and flat prior to making their maximum voluntary flexion, this allowed the system to record the maximum (Max) and minimum (Min) raw ADC values collected while all of the sensors were deflected through the full range capable of being recorded by the sensors. Both of these Max and Min values were used to normalize the raw sensor output:

$$V_{norm}=\frac{Vraw-Vmin}{Vmax-Vmin}$$

where V_{norm} is a normalized sensor reading (a number between 0 & 1), V_{raw} is the instantaneous raw adc reading, V_{min} and Vmax are the lower & upper limit values calibrated for each finger's adc output. The mapped value is based on linear interpolation to determine the estimated angle of rotation based on normalized value.

$$\theta_{estimated}=V_{norm}\times\theta_{max}$$

θest is calculated from the combination of the maximum ROM for the user, θmax, and the max flexion ROM in the static phase of calibration. The total of these values will produce a calculated agap value, which represents the amount of flexion to be attributed to the user∞s joint based on his/her ROM, in order for the user to use the gauntlet with the maximum capability for movement. As the child performed various instructed movements (flexion/extension, abduction/adduction, circumduction) during the dynamic calibration phase, the system recorded individualized motion baselines, based on variations among children (i.e., differences in hand size and flexibility of the joints, as well as remaining motor functions due to hemiplegia).

The glove sensors and the ESP32 microcontroller were electrically connected to each other using male-to-female, jumper wires in order to achieve a stable and consistent electrical connection through prototyping and clinical testing phases. The system was powered by an integrated, rechargeable lithium ion battery module in the glove assembly, thus alleviating the need to be connected to a power source while being used, thereby allowing for unrestricted, wireless rehabilitation in clinical and home environments. Also, the battery pack was chosen to provide the required amount of energy to keep the system operational for long periods of time during therapy sessions; the duration of battery usage was estimated by the following calculation.

$$T_{battery} = \frac{C_{battery}}{I_{system}}$$

This means that the glove system can be used continuously for up to "X" hours based on the current (mA) required to run the glove and how much the battery can hold (mAh). The fact the glove system uses a rechargeable battery makes it less expensive to use than a disposable battery and allows for easy transport and safe daily use by children in their homes or clinics, plus it eliminates the extra overhead of having to purchase new disposable batteries to replace used ones regularly.

2.1.2 Data Collection and Data Processing

Data collection begins with the creation of a benchmark dataset. Healthy children provided standardized hand movements with the goal of establishing normative ranges for finger flexion, extension, abduction, adduction, and circumduction. Data was also obtained from the unaffected hand of hemiplegic children, allowing the system to create personalized exercises based on the functional abilities of each individual child. Without utilizing data from the unaffected hand, the challenge would be to objectively base rehabilitation on normative averages alone, which fail to capture the unique motor capacity of each child.

The sensor architecture adopted a dual-modality approach to capture the full kinematic complexity of the five therapeutic movements. Flex sensors embedded in the glove were used to measure finger flexion and extension, capturing angular displacement in the sagittal plane. For abduction, adduction, and circumduction — movements that occur across multiple planes and involve compound rotational trajectories that flex sensors alone cannot reliably resolve — the MPU-9250 Inertial Measurement Unit (IMU) was employed. The MPU-9250 integrates a three-axis accelerometer, a three-axis gyroscope, and a three-axis magnetometer, providing a rich nine-degree-of-freedom (9-DOF) signal stream that enables accurate tracking of lateral finger spread, convergence, and rotational arc movements.

Raw signals provided by both sensor modalities are inherently noisy and require filtering prior to further processing. A Kalman filter was applied to smooth the angular trajectories of continuous movements captured by both the flex sensors and the MPU-9250. The Kalman filter operates through a two-step predict-update cycle governed by the following equations. In the prediction step, the prior state estimate and error covariance are computed as:

$$\hat{\theta}_k^- = A\hat{\theta}_{k-1} + Bu_k$$
$$P_k^- = AP_{k-1}A^T + Q$$

where $\hat{\theta}_k^-$ is the predicted state estimate of the joint angle at time step k, A is the state transition matrix, B is the control input matrix, u_k is the control input, P_k^- is the predicted error covariance, and Q is the process noise covariance matrix. In the update step, the Kalman gain and the corrected state estimate are computed as:

$$K_k = P_k^- H^T (HP_k^- H^T + R)^{-1}$$
$$\hat{\theta}_k = \hat{\theta}_k^- + K_k(z_k - H\hat{\theta}_k^-)$$
$$P_k = (I - K_k H)P_k^-$$

where K_k is the Kalman gain, H is the observation matrix, R is the measurement noise covariance, z_k is the actual sensor measurement at time step k, and I is the identity matrix. The Kalman filter iteratively refines the angular displacement estimate by balancing reliance on the predictive model against the noisy sensor observation.

For the MPU-9250, orientation estimation was performed by fusing the accelerometer, gyroscope, and magnetometer readings using a complementary filter. The gyroscope-integrated angle and the accelerometer-derived angle were fused as:

$$\hat{\phi}_k = \alpha\left(\hat{\phi}_{k-1} + \omega_{gyro,k} \cdot \Delta t\right) + (1 - \alpha)\phi_{accel,k}$$

where $\hat{\phi}_k$ is the fused orientation estimate at time step k, $\omega_{gyro,k}$ is the angular rate measured by the gyroscope, $\phi_{accel,k}$ is the tilt angle derived from the accelerometer readings, Δt is the sampling interval, and α is the complementary filter coefficient that governs the weighting between the gyroscope integration and the accelerometer correction, typically set close to 1 to prioritize the gyroscope for dynamic movements while relying on the accelerometer for drift correction over longer durations.

A Moving Average (MA) filter was additionally applied to remove high-frequency jitter caused by rapid fluctuations in both the flex sensor and MPU-9250 readings. The moving average output at each time step is given by:

$$\bar{\theta}_k = \frac{1}{N}\sum_{i=0}^{N-1} \theta_{k-i}$$

where $\bar{\theta}_k$ is the smoothed angular displacement at time step k, N is the window size defining the number of samples averaged, and θ_{k-i} are the preceding raw angular displacement values within the window.

Following noise removal, the continuous signal was segmented into discrete windows corresponding to individual movement instances. A sliding window segmentation approach was applied, where each window of length W samples with an overlap stride S was extracted as:

$$\mathbf{x}_j = [\theta_{jS}, \theta_{jS+1}, \ldots, \theta_{jS+W-1}]$$

where $\mathbf{x}_j$ is the j-th extracted window segment, and each windowed segment was subsequently assigned to one of the five target movement categories: flexion, extension, abduction, adduction, and circumduction.

Feature extraction was then performed on each segmented window. The instantaneous angular velocity of each finger joint was computed as the first-order discrete derivative of the smoothed angular displacement:

$$\omega_k = \frac{\bar{\theta}_k - \bar{\theta}_{k-1}}{\Delta t}$$

where ω_k is the angular velocity at time step k and Δt is the sampling interval in seconds. The angular acceleration was subsequently derived as the rate of change of angular velocity:

$$\alpha_k = \frac{\omega_k - \omega_{k-1}}{\Delta t}$$

where α_k is the angular acceleration at time step k. For abduction and adduction, the lateral angular displacement captured by the MPU-9250 in the coronal plane was extracted directly from the fused orientation estimate $\hat{\phi}_k$, with the peak lateral deviation from the neutral hand position used as the primary discriminating feature between the two opposing movements. For circumduction, which involves a continuous compound rotational movement traversing flexion, abduction, extension, and adduction in a sequential arc across multiple planes, the trajectory curvature was computed from the 3-DOF orientation data provided by the MPU-9250 to capture the spatial continuity of the rotational path:

$$\kappa_k = \frac{|\ \omega_k\ |}{(1+\bar{\theta}_k^2)^{3/2}}$$

where κ_k is the curvature of the angular trajectory at time step k, providing a distinctive multi-planar temporal signature that differentiates circumduction from the four cardinal plane movements. The hold duration for sustained directional gestures such as abduction and adduction was computed as:

$$T_{hold} = t_{release} - t_{onset}$$

where T_{hold} is the duration for which a movement was maintained beyond its threshold, t_{onset} is the timestamp at which the movement was detected to begin, and $t_{release}$ is the timestamp at which the angular displacement returned below the movement threshold. The collection of these feature dimensions — bending angles, fused orientation estimates, angular velocity, angular acceleration, trajectory curvature, and hold duration — drawn jointly from the flex sensor pipeline and the MPU-9250 formed a comprehensive multimodal feature representation that enabled thorough dataset construction for training and subsequent movement recognition and classification using the LSTM-based machine learning model.

2.1.3 Machine Learning Model Development

The system employs dynamic gesture recognition models. For dynamic gestures, such as sequential tapping, Long Short-Term Memory (LSTM) networks are applied to capture temporal dependencies in movement sequences [4].

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

LSTM Gate Equations:

$$\begin{aligned}
\mathrm{f}_t &= \sigma\left(W_f \mathrm{x}_t + U_f \mathrm{h}_{t-1} + \mathrm{b}_f\right) \\
\mathrm{i}_t &= \sigma(W_i \mathrm{x}_t + U_i \mathrm{h}_{t-1} + \mathrm{b}_i) \\
\mathrm{o}_t &= \sigma(W_o \mathrm{x}_t + U_o \mathrm{h}_{t-1} + \mathrm{b}_o) \\
\tilde{\mathrm{c}}_t &= \tanh\,(W_c \mathrm{x}_t + U_c \mathrm{h}_{t-1} + \mathrm{b}_c) \\
\mathrm{c}_t &= \mathrm{f}_t \odot \mathrm{c}_{t-1} + \mathrm{i}_t \odot \tilde{\mathrm{c}}_t \\
\mathrm{h}_t &= \mathrm{o}_t \odot \tanh\,(\mathrm{c}_t)
\end{aligned}$$

Output Layer:

$$\hat{\mathrm{y}} = \mathrm{softmax}(W_{out} \mathrm{h}_T + \mathrm{b}_{out})$$

Loss Function:

$$\mathcal{L} = -\sum_{c=1}^{C} y_c \log\,(\hat{y}_c)$$

Evaluation Metrics:

$$\text{Accuracy} = \frac{TP + TN}{TP + TN + FP + FN}$$
$$\text{Precision} = \frac{TP}{TP + FP}$$
$$\text{Recall} = \frac{TP}{TP + FN}$$
$$\text{F1-score} = 2 \times \frac{\text{Precision} \times \text{Recall}}{\text{Precision} + \text{Recall}}$$

2.1.4 Virtual Reality Game Design and Integration

The rehabilitation exercises are embedded within a gamified VR environment that called Magic Quest . This story-based game provides a setting that takes children into a fantasy world where finger motions are used to create magic spells and open runes and other enchanted objects. Each type of finger motion corresponds to a specific action in the game: finger flexion is used to make a magical fist that captures glowing orbs, finger extension creates a magical energy field to reveal hidden paths, finger abduction bends a magical barrier by pointing your fingers in the same direction as the generated energy beams, finger adduction connects magical materials by touching your fingers to each other, and finger circumduction traces a magic circle to create a spell that unlocks the storyline and gives access to powerful magical runes. Specifically, each of these therapeutic exercises is designed to be included in a meaningful narrative experience so that performing the motion feels purposeful and rewarding rather than like a clinical activity. This will help children maintain their internal motivation to perform repeated therapeutic repetitions for each rehabilitation session.

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

2.1.5 Feedback and Motivation Live

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

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

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 Flex/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 Fingers
- 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

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

2.2 Approach

2.2.1 Data collection

The training and validation processes used for creating the machine learning model to classify the finger 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 had been 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 Finger movements such as resting position or steady, flexion, extension, abduction, adduction and cirucumduction, 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

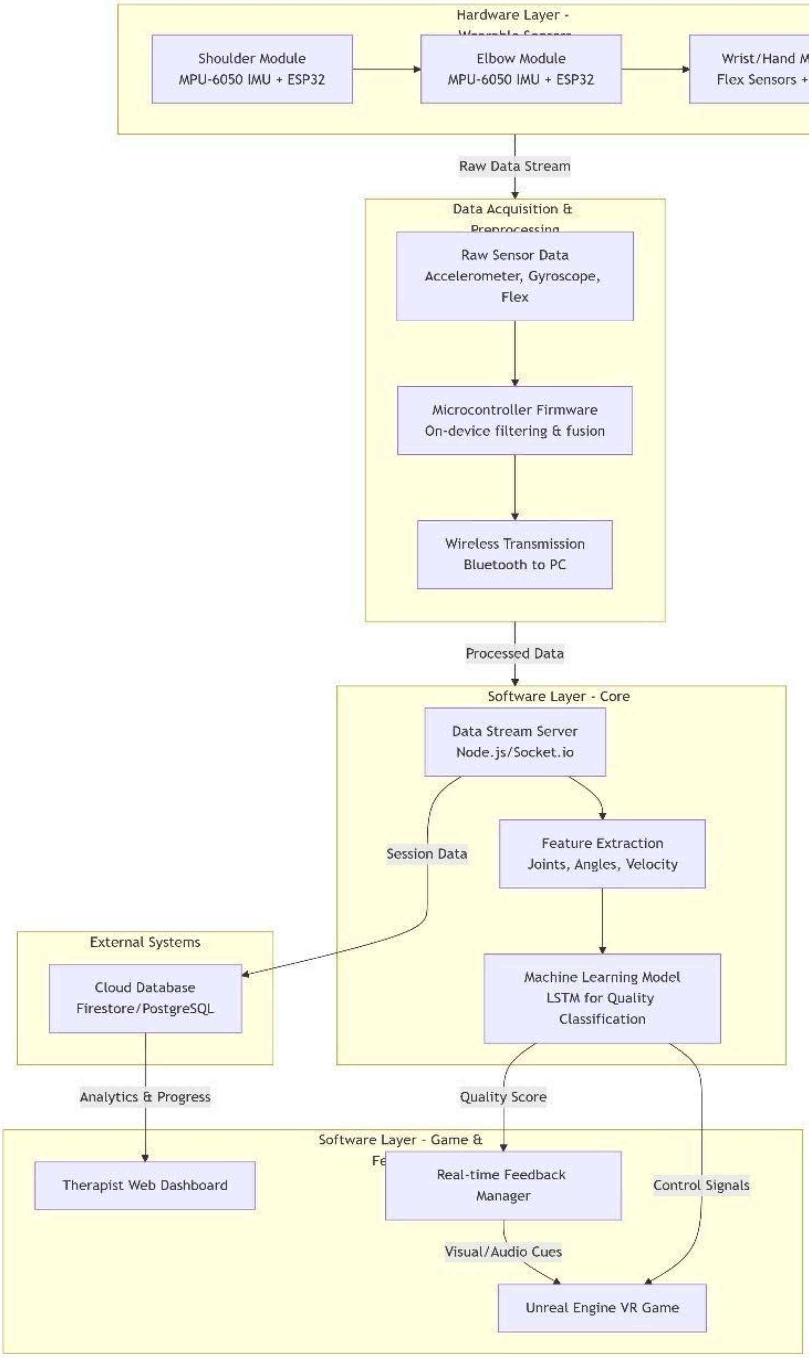
A purpose-built IoT data collection device was built in order to extract Finger j motion signals. This device comprised five Flex sensors and one MPU9250 IMU sensor with a low weight 3D printed flexible glove, coupled with an ESP32 microcontroller. The ESP32 board was plugged into the computer via USB cable while collecting the finger 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 finger motions, analog signals indicating acceleration and angular velocities were generated by the MPU9250 IMU sensor and flexion extension get by the flex sensors. These signals went through a filter process, specifically, a Kalman filter applied on the ESP32, in order to get rid of noises and ensure a smooth signal output. The data obtained through the process was transmitted to the computer and saved for machine learning purposes.

Finger Movements Captured

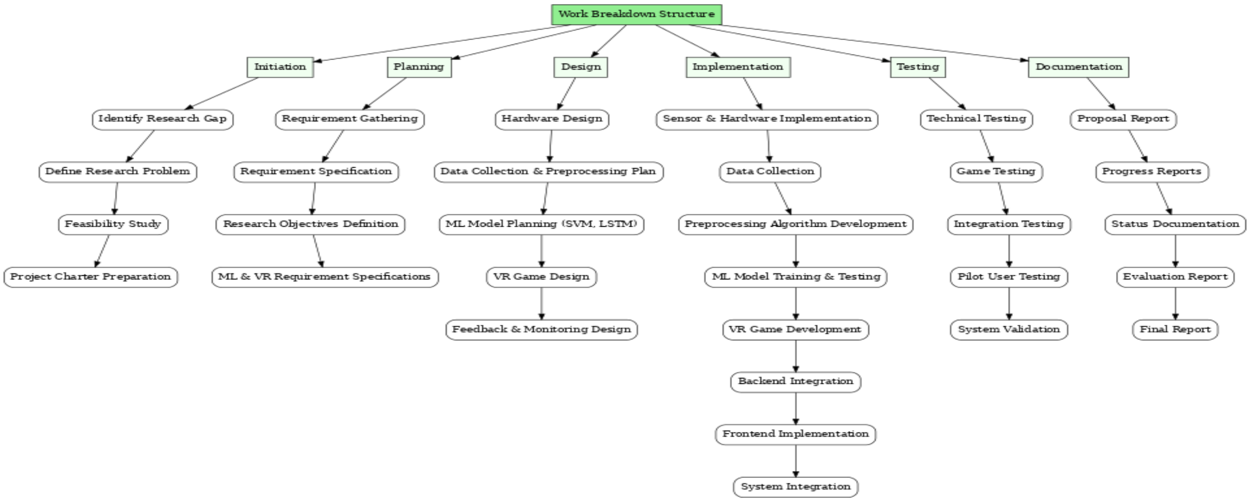
Steady: Neutral resting position
Flexion: Moving the Fingers upwards
Extension: Moving the Fingers downwards
Abduction: spreading the fingers apart, away from the midline of the hand.
Adduction: brings the fingers together, towards the midline of the hand
Circumduction: circular, cone-shaped movement of a digit produced by the sequential combination of flexion, abduction, extension, and adduction

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

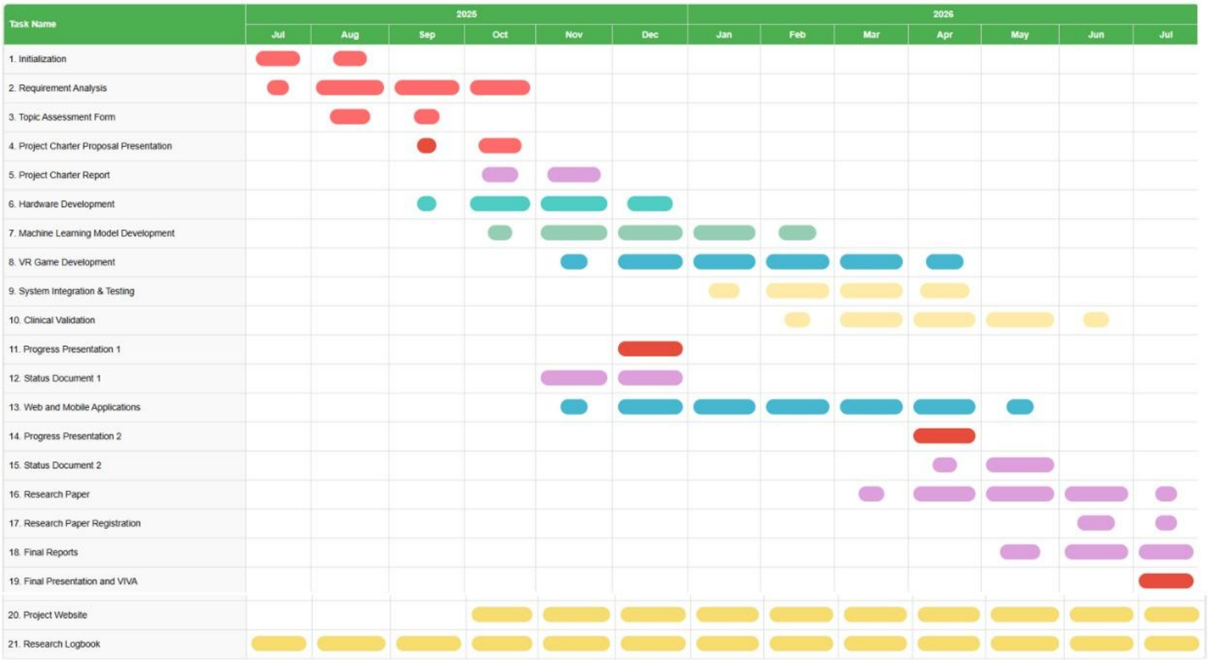
2.3 High-Level System Architecture Diagram



2.4 Work Breakdown Structure



2.5 Gantt Chart



2.6 Project Requirements that have been achieved

2.6.1 Functional Requirements

The Finger 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 fingers have to be performed in real time using sensors (Flex /MPU9250) attached to an elastic cuff and then to an ESP32 microcontroller. Such motions as flexion, extension, abduction, adduction, circumduction, and 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 finger movements from the sensor using machine learning models. 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 provides an immersive VR experience called Magic Quest: The Enchanted Fingers, where finger movements are linked directly to meaningful in-game actions that drive narrative progression throughout the magical world. Flexion closes the wizard's hand to cast powerful spells and capture glowing magical orbs floating across the enchanted realm, while extension spreads arcane energy across enchanted surfaces to reveal hidden pathways and unlock sealed doors barring the child's journey forward. Abduction directs energy beams outward by spreading the fingers apart to part mystical barriers and defeat approaching enchanted creatures, while adduction draws scattered magical elements together by converging the fingers to seal enchanted portals and restore balance to the magical world. Circumduction traces luminous spell circles in the air, activating powerful ancient runes and unlocking pivotal story progression milestones that advance the child deeper into the narrative. Each therapeutic finger movement is therefore deliberately embedded within a contextually meaningful and narratively consequential in-game interaction, ensuring that every repetition feels purposeful and rewarding rather than clinical. The benefits of VR gamification in pediatric rehabilitation include increasing patient engagement, promoting neuroplasticity, and improving motor learning opportunities, as the immersive and interactive nature of the virtual environment encourages sustained voluntary movement repetition, reinforces correct motor patterns through immediate multisensory feedback, and leverages the brain's capacity for activity-dependent neural reorganization to support meaningful functional recovery in children with hemiplegia.

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 and Flex 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 and Flex 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

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

2.10.2 Firmware and Data Handling Layer

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

2.10.3 Machine Learning Layer:

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

2.10.4. Game Development Layer:

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

2.10.5 Cloud and Monitoring Layer:

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

2.10.6. Mobile and Caregiver Interface Layer:

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

2.10.7. AI-driven Support Layer:

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

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

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:

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

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

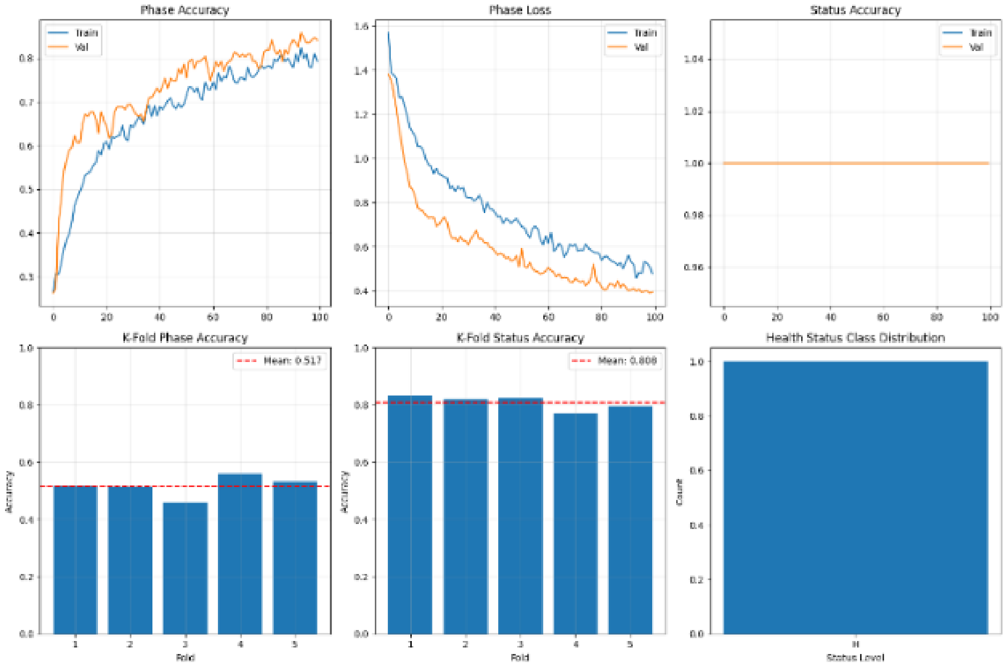
$$Recall = \frac{TP}{TP + FN}$$

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

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

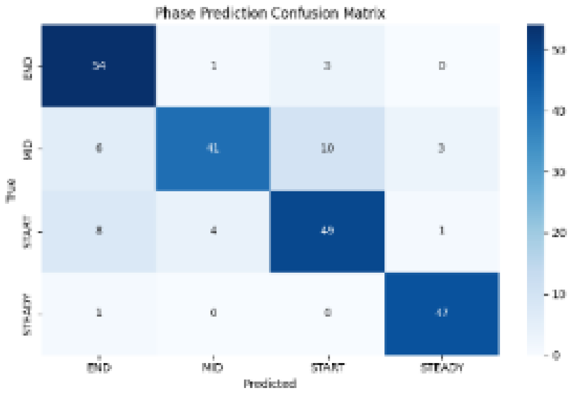
B. Movement Classification Performance

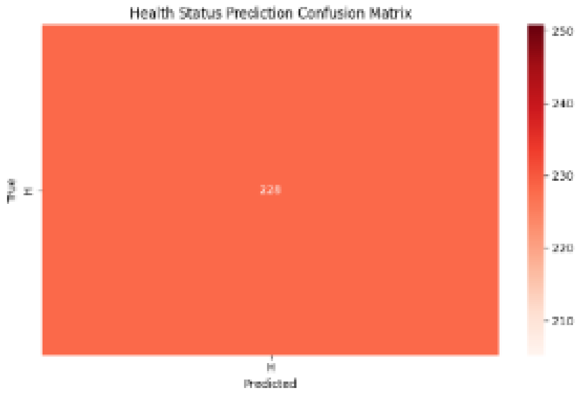
The LSTM model demonstrated high accuracy and robustness in recognizing upper limb movements.



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

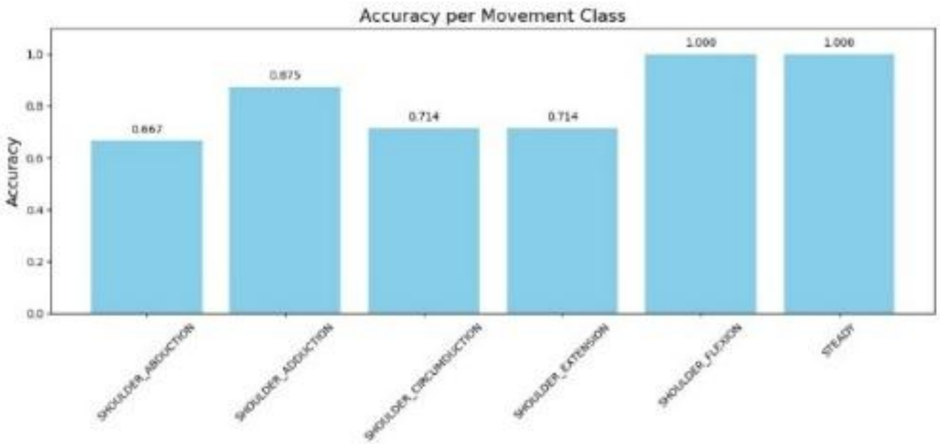
The low standard deviation and coefficient of variation (CV = 2.48%) indicate that the model is highly stable across folds, confirming strong generalization capability. Training and validation curves show consistent convergence, with minimal gap between training and validation accuracy, indicating no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

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

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

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