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VR Phantom Haven: Phantom Limb Pain Management Using Virtual Reality

B. Tech. Computer Engineering

By

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Shri Vile Parle Kelavani Mandal's
DWARKADAS J. SANGHVI COLLEGE OF ENGINEERING
(Autonomous College Affiliated to the University of Mumbai)
NAAC Accredited with "A" Grade (CGPA : 3.18)

University of Mumbai

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CERTIFICATE

This is to certify that the project entitled **"VR Phantom Haven: Phantom Limb Pain Management using Virtual Reality"** is a bonafide work of **"Gautam Mehendale" (60004200125), "Aditya Shah" (60004200148) & "Siddhi Muni" (60004200147)** submitted to the University of Mumbai in partial fulfillment of the requirement for the award of the degree of B.Tech. in Computer Engineering

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30.11.2023

TO WHOMSOEVER IT MAY CONCERN

I wish to convey that Phantom Limb pain is indeed a very real phenomenon, often presenting significant challenges to those affected.

The project "Phantom Limb Pain Management using Virtual Reality" under Dr Chetashri S. Bhadane can be a potential method to tackle this problem

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Project Report Approval for B.Tech.

This project report entitled VR Phantom Haven: Phantom Limb Pain Management Using Virtual Reality by Aditya Shah (60004200148), Siddhi Muni (60004200147), and Gautam Mehendale (60004200125) is approved for the degree of ***B.Tech. in Computer Engineering.***

Examiners

1.--

2.--

Date:

Place:

Declaration

I/We declare that this written submission represents my/our ideas in my/our own words and where others' ideas or words have been included, I/We have adequately cited and referenced the original sources. I/We also declare that I/We have adhered to all principles of academic honesty and integrity and have not misrepresented or fabricated or falsified any idea/data/fact/source in my/our submission. I/We understand that any violation of the above will be cause for disciplinary action by the Institute and can also evoke penal action from the sources that have thus not been properly cited or from whom proper permission has not been taken when needed.

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Abstract

Phantom limb pain (PLP) remains a persistent and challenging condition for amputees, with current treatment modalities often failing to provide sufficient relief. This study investigates the potential of virtual reality (VR) as a groundbreaking therapeutic approach for PLP management. The VR-based system incorporates features specifically tailored to address the complexities of PLP, including interactive interfaces, customizable environments, and real-time pain detection using machine learning models. By integrating various interactive elements, users can engage their phantom limb in meaningful ways, fostering a reconnection between their mind and body. Customizable virtual environments create immersive and soothing experiences, catering to individual preferences and promoting relaxation.

Moreover, the VR system incorporates gamification elements to enhance engagement and distraction from pain. Patients can participate in virtual activities that challenge and stimulate their phantom limb, providing a sense of accomplishment and control over their condition. Additionally, the system's adaptive nature allows for personalized therapy sessions, adjusting difficulty levels and activities based on the patient's progress and feedback.

A pilot study involving three PLP patients exposed them to the VR system for 30-45 minutes per session. Pain levels, assessed before and after VR exposure, demonstrated a significant reduction from an initial level of 3 to 0 after the session. Participants highlighted the engaging nature of the VR experience, contributing to improved relaxation and a sense of control over their phantom limb. These preliminary findings suggest VR as a safe, engaging, and potentially effective approach for PLP management. The customizable virtual environments allow patients to tailor therapy to their specific needs, enhancing overall well-being. Integrating machine learning models for real-time pain detection enhances the system's potential, ensuring continuous monitoring and therapy adjustment based on patient feedback.

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List of Abbreviations

Sr. No.	Abbreviation	Expanded form
i	PLP	Phantom Limb Pain
ii	VR	Virtual Reality
iii	MPS	Myofascial Pain Syndrome
iv	XAI	Explainable AI
v	BPI	Brachial Plexus Injuries
vi	TPI	Trigger Point Injections
vii	ICC	intraclass correlation coefficient

Chapter 1

Introduction

1.1 Description

Phantom Limb Pain (PLP) poses a unique and formidable challenge in the realm of medical conditions, where individuals who have undergone amputation continue to perceive sensations of pain in the absent limb. This intriguing phenomenon underscores the intricate connection between the brain and the sensory nervous system, which persistently transmits pain signals despite the physical absence of the limb. PLP's complexity extends beyond mere physical sensations, intertwining with intricate neurological processes that render it notably resistant to conventional pain management approaches.

Beyond the physical discomfort, PLP exerts a profound toll on mental and emotional well-being. The perpetual presence of pain, coupled with reminders of the lost limb, often precipitates feelings of frustration, depression, and anxiety. Furthermore, PLP can significantly impede daily activities, diminishing overall quality of life and exacerbating the challenges faced by amputees in adapting to their new circumstances.

Understanding the multifaceted nature of PLP necessitates a comprehensive approach that addresses both its physiological and psychological dimensions. Effective management strategies must thus not only target pain sensation but also endeavor to restore a sense of wholeness and functionality to affected individuals. This project endeavors to explore innovative interventions, such as virtual reality (VR), as a promising avenue for PLP management, while simultaneously probing the broader societal attitudes and perceptions surrounding amputees and PLP. Through interdisciplinary collaboration and holistic exploration, this project aspires to advance understanding, alleviate suffering, and foster a more empathetic and inclusive society for individuals grappling with PLP.

1.2 Problem Formulation

Phantom Limb Pain (PLP) affects a significant proportion of amputees, with varying estimates suggesting that up to 80% of individuals with amputations experience this condition at some point. This prevalence underscores the urgent need for effective management strategies to alleviate the burden of PLP on affected individuals. Moreover, PLP's impact extends beyond mere physical discomfort, with studies indicating its adverse effects on mental health, social functioning, and overall well-being. The complexity of PLP necessitates a nuanced approach that addresses its multifaceted nature and considers individual variations in symptoms and responses to treatment.

The pain associated with PLP can be persistent and severe, posing significant challenges to individuals' daily functioning and quality of life. Moreover, PLP's unpredictable nature further compounds the difficulties in managing this condition effectively. The limitations of traditional treatments, such as medication, nerve blocks, and therapy, highlight the need for innovative interventions that can provide sustainable relief while minimizing adverse effects. Additionally, the high variability in treatment outcomes underscores the importance of personalized approaches that take into account individual differences in PLP presentation and response to treatment modalities.

Addressing the gap in our understanding and ability to manage PLP effectively requires a multifaceted approach that integrates advancements in neuroscience, technology, and patient-centered care. By combining insights from basic science research with clinical expertise and patient perspectives, we can develop tailored interventions that target the underlying mechanisms of PLP while addressing the diverse needs and preferences of affected individuals. Moreover, fostering collaboration between healthcare providers, researchers, and policymakers is essential for advancing PLP research and ensuring the timely translation of discoveries into accessible and effective treatments for those in need.

1.3 Motivation

The urgent need for more effective treatments for PLP is motivated by the limitations of existing therapies, which often fail to address the multifaceted nature of phantom limb pain. Current approaches typically focus on symptom management without addressing underlying neurological changes. The motivation for this project stems from the potential of Virtual Reality (VR) technology to provide a comprehensive and immersive therapy that could remodel the neurological pathways associated with PLP, thus offering a more sustainable and effective management strategy.

1.4 Proposed Solution

The proposed solution for effectively managing Phantom Limb Pain (PLP) involves the integration of machine learning algorithms for pain detection and an adaptive virtual reality (VR) environment tailored to individual needs. The machine learning component utilizes biometric data collected through devices like the Apple Watch to extract features indicative of pain levels, such as heart rate variability, skin conductance, and motion data. Supervised machine learning techniques, such as Neural Networks, are then employed to classify pain levels based on these features, enabling real-time analysis and adjustment of the VR environment according to the user's current pain level.

The adaptive VR environment further enhances the therapeutic experience by customizing the virtual scenarios, sounds, and interactive elements based on user preferences and therapy requirements. An environmental customization algorithm dynamically adjusts the VR environment to enhance engagement and effectiveness, while a feedback loop ensures real-time adaptation based on user interactions and pain management effectiveness. This personalized approach allows for a tailored therapeutic experience that addresses the unique needs and responses of each individual.

The system's working involves a comprehensive architecture encompassing login and user authentication, session initiation, real-time operation, feedback and reporting mechanisms, and emergency protocols. Users, including patients and therapists, securely access personalized therapy settings, initiate VR sessions, and undergo continuous physiological data collection during sessions. Therapists can remotely monitor sessions in real-time, adjust settings, and intervene if necessary. End-of-session summaries provide valuable insights into session effectiveness, facilitating therapist review and adjustments to the therapy plan for future sessions. Additionally, safety mechanisms ensure patient well-being by automatically ending sessions in case of extreme physiological responses. This holistic approach leverages advanced VR development platforms and hardware, integrated with machine learning libraries, to deliver a comprehensive and effective solution for managing PLP.

1.5 Scope of the Project

The scope of this project encompasses the design, development, and evaluation of the VR application over a series of phases. Initially, the project will focus on creating a prototype that incorporates basic interactive and monitoring features. Subsequent phases will expand on the complexity and personalization of the VR environments, followed by pilot testing with a select group of PLP patients. Evaluation metrics will include changes in pain intensity, patient feedback on the VR experience, and psychological well-being assessments. The ultimate goal is to validate the VR system as a viable tool for PLP management and to establish a foundation for its broader application in other chronic pain conditions.

Chapter 2

Review of Literature

[1] X-reality for phantom limb management for amputees: A systematic review and meta-analysis: This study explores the use of X-reality technologies (virtual, augmented, and mixed reality) for managing phantom limb pain in amputees, with a focus on various interventions and their impact on pain reduction. This survey collected information via search strategy, screen strategy,data extraction and meta analysis. It also includes game themes, gameplays and designing various tasks. The mean difference between the pain levels before and after X-reality interventions was 2.30 (95% CI: -3.38 to -1.22). Interventions using virtual reality were highly successful, with a mean difference of 2.83 (95% CI: -4.43 to -1.22). The study requires generalizability of these interventions and diverse study designs.

[2] Using Virtual Reality Exposure Therapy in Pain Management: A Systematic Review and Meta-Analysis of Randomized Controlled Trials: This study evaluated how well virtual reality (VR) worked for treating different kinds of pain in various age groups. It was discovered that VR can successfully lower anxiety, pain unpleasantness, and pain intensity in individuals of all ages. It did, however, not considerably increase pain threshold and demonstrated only moderate efficacy in treating long-term pain, such as persistent low back pain and pain associated with cancer. A comprehensive analysis of 31 randomized controlled studies released up through October 2020 was carried out by the researchers. The Cochrane Library, PubMed, EMBASE, and Web of Science were among the electronic resources they reviewed to find pertinent papers that discussed the application of VR for pain management. When compared to control groups, VR significantly reduced the level of pain, with a larger impact shown in patients who were younger. Additionally, VR led to decreased anxiety, less unpleasant pain, slower heart rates, and quicker dressing changes. Virtual reality proved to be useful in treating acute pain, but it was less successful in treating chronic pain problems such as cancer-related pain and chronic low back pain. The theorized studies are required to determine whether VR therapy may be beneficial for particular subgroups of chronic pain patients.

[3] Virtual reality therapy for myofascial pain: Evolving towards an evidence-based non-pharmacological adjuvant intervention: This study discusses the possibility of virtual reality (VR) therapy as a non-pharmacological adjuvant treatment for the widespread and debilitating chronic pain condition myofascial pain syndrome (MPS). VR has demonstrated potential in neuroplasticity and acute pain management, but it has not been clinically evaluated in the treatment of MPS, and the study highlights the need for more research in this area. In order to control MPS, the study suggests evaluating the effectiveness of routine VR therapy sessions and contrasting their results with simulated VR. To demonstrate the possible advantages of VR therapy, it makes reference to a study conducted on patients with chronic low back pain. It does, however, recognize methodological limitations with regard to the selection of patients and the dependence on patient-reported data. Virtual reality therapy has demonstrated potential in enhancing motivation, encouraging exercise, and lowering pain-related interference in long-term pain problems such as persistent low back pain. The report emphasizes the necessity for more trials focused on MPS that assess VR therapy's efficacy as a supplement to traditional therapies like trigger point injections (TPIs). To determine VR therapy's relative efficacy and role in the treatment of MPS, research contrasting it with standard-of-care therapies employed by pain practitioners is required.

[4] Virtual Reality combined with Robotic facilitated movements for pain management and sensory stimulation of the upper limb following a Brachial Plexus injury: A case study: This study investigates how individuals with brachial plexus injuries (BPIs) may benefit from immersive virtual reality (VR) with haptic feedback to improve function and lessen upper limb pain. VR has the potential to be used in BPI rehabilitation, as evidenced by the single case study, which reports a 50% decrease in discomfort and an improvement in range of motion. The paper includes a single case study of a patient who had a complicated mix of neuropathic pain and phantom limb discomfort. As a non-invasive solution, VR with haptic feedback was employed to evaluate its effects on pain relief and function enhancement. Following the use of immersive VR with haptic feedback, the patient with BPI saw a significant 50% reduction in reported pain levels, according to the case study. An early formation of the thumb representation on the stump is suggested by an examination of the sensory phantom map, which may be advantageous for prosthetic use. The study emphasizes how little is known about

the application of virtual reality (VR) to brachial plexus injuries. Larger sample sizes and additional research are required to validate its efficacy in this particular patient population.

[5] A Virtual Reality Intervention for the Treatment of Phantom Limb Pain: Development and Feasibility Results: This research created and evaluated a virtual reality (VR) therapy for veterans with phantom sensations and limb pain (PLP). It was discovered that subjects gave the VR treatment high ratings, and that this led to a considerable decrease in the intensity of PLP and unpleasant phantom experiences. After completing a baseline assessment, fourteen participants received virtual reality therapy that was similar to mirror therapy for PLP. Measures were taken both before and after the therapy to evaluate how the PLP, phantom sensations, and user experiences—such as helpfulness, realism, immersion- changed. 93% of individuals reported unpleasant phantom sensations and 57.1% felt PLP prior to the VR therapy. Following the intervention, phantom sensations (reported by 28.6% of the participants) and PLP intensity (reported by 28.6% of the participants) were significantly reduced. There were not many veterans in the study's limited sample. Increasing the study's sample size and diversifying the population may yield more thorough insights regarding VR's efficacy for PLP.

[6] A review of the management of phantom limb pain: challenges and solutions: This study sought to evaluate the difficulties experienced by physicians and provide a thorough assessment of therapies for phantom limb pain (PLP), a condition that affects a large number of amputees. A first-line treatment for PLP is difficult to establish due to the low quality of evidence overall, despite the review identifying 38 treatments. Using "phantom limb" as a MeSH keyword, the researchers searched a number of databases, including MEDLINE, EMBASE, CINAHL, British Nursing Index, Cochrane, and psycINFO, to find therapies. To locate pertinent studies, secondary searches combined "phantom limb" with each treatment. The GRADE method was used to evaluate the quality of the evidence. One excellent trial employing repetitive transcutaneous magnetic stimulation was identified for the review; it demonstrated a statistically significant decrease in pain at day 15 but no change at day 30. Significant findings for gabapentin, ketamine, and morphine were reported by single trials of moderate quality; nevertheless, bias issues were raised in these reports. The use of mirror therapy and related treatments was not well-supported by research. Due to the generally poor quality of the data, the study emphasizes the lack of a definitive first-line treatment for PLP. This highlights the necessity for more thorough research in this field.

[7] Recent advances in understanding and managing phantom limb pain: This narrative review evaluates mechanism-based treatments from the previous five years and examines recent developments in the treatment of post-amputation phantom limb pain (PLP). However, none of the examined treatments consistently outperformed the control circumstances, which is probably because PLP is governed by a variety of intricate mechanisms. Randomized controlled trials of PLP therapies published in the last five years were examined for this review. It concentrated on treatments including mirror therapy, virtual and augmented reality, targeted muscle reinnervation, repetitive transcranial magnetic stimulation, imaginal phantom limb exercises, and eye movement desensitization and reprocessing therapy. None of the examined treatments outperformed control conditions in treating PLP consistently, according to the review. Due to their tiny sample sizes, most therapy trials were probably underpowered. The intricacy of PLP, which is influenced by several different pathways, makes treatment very difficult. The study highlights the necessity of research methodologies that group patients into groups according to common characteristics and assess the effectiveness of treatment within these groups while taking into account the various mechanisms that lead to PLP.

[8] The effect of mirror therapy on the management of phantom limb pain: In this study, the role of nurses in mirror therapy implementation was underlined as it looked at the effects of the treatment on phantom limb pain (PLP) in amputee patients. Mirror therapy has been shown to considerably lessen PLP severity, especially in non prosthetic patient populations. Fifteen amputee patients with PLP participated in a quasi-experimental study. Following a 40-minute practical mirror therapy training session, patients were instructed to practice at home for a period of four weeks. They used a Numeric Pain Intensity Scale to record the daily severity of their PLP. After four weeks of practice, mirror treatment significantly decreased the severity of PLP. According to the study, patients who did not wear prostheses benefited more from mirror treatment. More research may be needed to determine the precise duties and responsibilities of nurses in putting mirror therapy into practice and providing support for it as part of all-encompassing patient care.

[9] Characteristics of Phantom Limb Pain Alleviated with Virtual Reality Rehabilitation: This study examined the effectiveness of virtual reality (VR) rehabilitation for Phantom Limb Pain (PLP) in 19 patients. VR significantly improved movement representation and reduced PLP

intensity, especially for pain related to distorted limb movements. The study categorized PLP characteristics into two factors: "somatosensory-related" and "kinesthesia-related." VR's effectiveness correlated with "kinesthesia-related" characteristics. Future research could explore VR's long-term effects, compare it with other treatments, personalize therapy, delve into underlying mechanisms, and assess its applicability to a broader range of PLP patients. The study included 19 participants with Phantom Limb Pain (PLP). PLP characteristics were assessed using the Short-Form McGill Pain Questionnaire (SF-MPQ). Patients underwent 20-minute VR rehabilitation sessions featuring mirror-reversed graphics to simulate phantom limb movement. Data collection involved measuring pre- and post-VR rehabilitation movement representation and PLP intensity. Factor analysis categorized PLP characteristics into "somatosensory-related pain characteristics" and "kinesthesia-related pain characteristics. VR rehabilitation reduced PLP intensity. PLP characteristics were categorized into "somatosensory-related" and "kinesthesia-related" factors. VR's effectiveness in reducing PLP correlated with "kinesthesia-related" characteristics, not "somatosensory-related" ones. The study's sample size of 19 patients was relatively small, highlighting the need for future research with larger and more diverse cohorts. Additionally, investigating the long-term benefits of VR rehabilitation is crucial to determine its sustained effects. To enhance treatment comparisons, future studies could incorporate control groups.

[10] Factors associated with phantom limb pain: This multicenter longitudinal study examined phantom limb pain (PLP) prevalence and associated factors in 134 amputees. Six months post-amputation, lower limb amputees had the highest PLP rates, while upper limb amputees experienced peak PLP at 1.5 years. Women reported higher PLP rates than men. Over time, lower limb amputees increased prosthetic use. Logistic regression showed that being male, having a lower limb amputation, and time since amputation were protective factors against PLP. The objective of the research is to analyze PLP prevalence and associated factors in amputees. It includes 134 amputees as participants, with 85 providing pre- and post-amputation questionnaire responses. Preoperative data included patient characteristics and amputation details. Follow-up questionnaires assessed PLP, prosthetic use, and walking distance at six months, 1.5 years, and 2.5 years post-amputation. The research observed that peak PLP occurred at six months for lower limb amputees and at 1.5 years for upper limb amputees and women reported higher PLP rates. Lower limb amputees increased prosthetic use, peaking at 1.5 years. Logistic regression revealed that being male, having a lower limb amputation, and

time since amputation were protective factors against PLP. The research should include a more diverse group of amputees, especially those with upper limb amputations. Additionally, an investigation on how prosthetic design and usage patterns impact PLP for improved rehabilitation and care must be carried out.

[11] VirHab - A virtual reality system for treatment of chronic pain and disability: This study explores a virtual reality (VR) system for treating upper extremity pain and impairment, targeting conditions like CVA and CRPS. The VR system, based on motion capture and image processing, replaces the impaired arm with a virtual one on the screen. Patients make small movements with their affected arm, witnessing their virtual arm perform full-range movements. The hypothesis is that this VR intervention induces brain plasticity, potentially reducing pain and enhancing limb function. The research evaluates the therapeutic potential of a VR system for upper extremity pain and impairment and utilizes motion capture and image processing to create a virtual environment where patients see themselves with a virtual arm. Patient interaction is such that, when the patients make small movements with their affected arm, end up observing their virtual arm performing full-range movements. To measure the outcome, the research employs clinical and neuroimaging assessments to gauge pain levels and functional improvements. The paper outlines the development of the VirHab system, citing neurophysiological and clinical evidence. It mentions a prior feasibility study with an earlier prototype and an ongoing randomized controlled study with CVA patients. Future plans involve exploring applications for other conditions like CRPS and TBI, adapting the system for lower extremities, and integrating it with EEG and fMRI techniques to study mirror neurons. The focus is on clinical and scientific contributions to understanding mirror neuron networks. While the paper discusses the VirHab system's rationale and initial feasibility study, there's a gap in comprehensive clinical evidence. Future research should aim to conduct more extensive and rigorous clinical trials to establish the system's effectiveness across various patient populations and conditions. Moreover, the paper alludes to a prior feasibility study with an earlier prototype but lacks specifics. Providing insights into the outcomes and challenges faced in this preliminary study would help inform the system's development.

[12] Reliability of phantom pain relief in neurorehabilitation using a multimodal virtual reality system: This study explores the reliability of relieving phantom limb pain through a multimodal virtual reality system. Six patients with brachial plexus avulsion or arm amputation

used the system for a reaching task. Phantom limb pain reduction was assessed using a pain questionnaire. The experiments were conducted twice on different days. The study found strong reliability (ICC of 0.737) and a statistically significant 50.2% average reduction in pain, indicating the effectiveness of neurorehabilitation with the virtual reality system. In this study, a multimodal virtual reality system was employed to examine the reliability of alleviating phantom limb pain. Six patients with brachial plexus avulsion or arm amputation participated in a reaching task within a virtual environment, controlling a virtual phantom limb using their intact limb. Phantom limb pain intensity was assessed through a short-form McGill pain questionnaire. The experiments were conducted twice, on separate days, with at least a four-week gap between sessions for each patient. Reliability was determined using Fisher's intraclass correlation coefficient (ICC), with a strong ICC of 0.737 indicating high reproducibility. On average, participants experienced a statistically significant 50.2% reduction in pain, affirming the effectiveness of neurorehabilitation with the multimodal virtual reality system. The study assesses the effectiveness of a rehabilitation task in relieving phantom limb pain using a multimodal virtual reality system. The pain intensity is evaluated before and after the task through the McGill pain questionnaire. The reliability of pain reduction is measured using Fisher's intraclass correlation coefficient (ICC). The study demonstrates a strong ICC of 0.737, indicating high reproducibility of pain reduction. The average reduction rate for participants is 50.2%, significantly different from 0 ($p<0.001$). However, the reduction rates tend to decrease in the second test, suggesting a potential distraction effect as the novelty of the system wears off. The standard deviation of reduction rates among participants is not small, indicating variability in pain relief, possibly due to medical details and individual brain mechanisms. The study does not quantify the duration of analgesic effects produced by the task. Further research could investigate the sustainability of pain relief provided by the system over time. The study is limited by the small sample size of six participants. Expanding the study to include a larger and more diverse group of patients with phantom limb pain would enhance the generalizability of the findings.

Chapter 3

SYSTEM ANALYSIS

System analysis is a crucial phase in the development of any innovative solution, particularly one as intricate as a Virtual Reality (VR) system tailored for Phantom Limb Pain (PLP) management. This analysis delves into the functional and non-functional requirements essential for ensuring the efficacy, reliability, and usability of the proposed VR application. By delineating the system's functionalities, performance benchmarks, and specific requirements, this analysis lays the groundwork for the subsequent design, development, and evaluation phases. Additionally, it addresses key considerations such as user authentication, pain level detection, interactive VR environments, real-time feedback mechanisms, session reporting, safety monitoring, and the integration of hardware and data analytics. Through a comprehensive system analysis, this project aims to deliver a robust and patient-centered VR solution poised to revolutionize PLP management while adhering to the highest standards of usability, reliability, and security.

3.1 Functional Requirements

The functional requirements of the project outline the specific capabilities and functionalities that the system must have to fulfil its objectives effectively

The functional requirements of the project entail the development of algorithms for pain detection using machine learning techniques and the creation of an adaptive virtual reality (VR) environment. These algorithms must analyze biometric data in real-time, adjusting the VR environment dynamically based on user preferences and therapy needs. Additionally, the system architecture should support user authentication, session initiation, and real-time operation, allowing for continuous physiological data collection and therapist monitoring. Feedback mechanisms are essential for generating session summaries, enabling therapist review and adjustments to therapy plans, while safety protocols ensure patient well-being by automatically ending sessions if necessary. Overall, these requirements aim to deliver a personalized and effective solution for managing Phantom Limb Pain (PLP) by leveraging advanced technologies and methodologies.

1. User Authentication: Secure login for patients and therapists to access personalized settings and therapy sessions.
2. Pain Level Detection: Utilize machine learning models to detect and monitor changes in pain levels in real-time during VR sessions.
3. Interactive VR Environment: Offer an interactive virtual reality world that patients can navigate, which includes customizable environments tailored to individual therapy needs.
4. Real-Time Feedback: Provide immediate feedback to users based on their interaction within the VR environment and physiological data collected during the session.
5. Session Reporting: Automatically generate detailed reports at the end of each session that summarize user activities, physiological data, and observed changes in pain levels for review by healthcare providers.
6. Safety Monitoring: Continuously monitor physiological indicators (e.g., heart rate, skin conductance) to ensure patient safety during VR exposure.

3.2 Non-Functional Requirements

The non-functional requirements of the project encompass various aspects crucial for the successful implementation and operation of the PLP management solution. These include performance requirements to ensure the system operates efficiently, with minimal latency in data processing and VR environment adjustments. Reliability requirements are essential to guarantee the system's stability and availability, with measures in place to mitigate potential downtime or system failures. Security requirements are paramount to safeguard sensitive patient data and ensure user authentication and authorization mechanisms are robust and compliant with privacy regulations. Usability requirements focus on creating an intuitive and accessible user interface, allowing both patients and therapists to navigate the system easily and engage in therapy sessions comfortably. Lastly, scalability requirements address the system's ability to accommodate growth and increased usage over time, ensuring it can adapt to evolving needs and accommodate a larger user base if necessary. By fulfilling these non-functional requirements, the PLP management solution can provide a reliable, secure, and user-friendly experience for all stakeholders involved.

1. Usability: The VR interface must be user-friendly and easily navigable by patients with varying degrees of tech-savviness.
2. Reliability: The system should consistently perform as expected, with minimal downtime or errors during critical therapy sessions.

3. Performance: Response times must be fast enough to ensure real-time interaction and feedback within the VR environment.
4. Scalability: The system should be capable of handling an increasing number of users as it is deployed to a broader audience.
5. Security: Ensure high levels of data security, especially with sensitive patient data, complying with healthcare regulations like HIPAA.
6. Accessibility: Design the VR application to be accessible to users with different types of disabilities, including those related to mobility and vision.

3.3 Specific Requirements

The specific requirements for the VR system designed for PLP management are crucial for its functionality and effectiveness. These requirements include seamless hardware integration, customizable VR environments, adaptive therapy intensity based on real-time pain assessments, advanced data analytics for biometric sensor data, and a user-friendly therapist interface. By meeting these requirements, the system aims to provide personalized and effective pain management solutions for PLP sufferers, empowering both patients and therapists with innovative tools and capabilities.

1. Hardware Integration: The system must integrate seamlessly with VR headsets and other hardware like biometric sensors (e.g., Apple Watch) for real-time data collection.
2. Customization: Ability to customize VR environments based on therapeutic needs and patient preferences.
3. Adaptability: The application should adapt the therapy intensity and activities based on real-time pain level assessments.
4. Data Analytics: Incorporate advanced data analytics for processing and interpreting complex datasets from biometric sensors.
5. Therapist Interface: Provide therapists with tools to remotely control and adjust VR sessions and review comprehensive session reports.

3.4 Use-Case Diagrams and Description

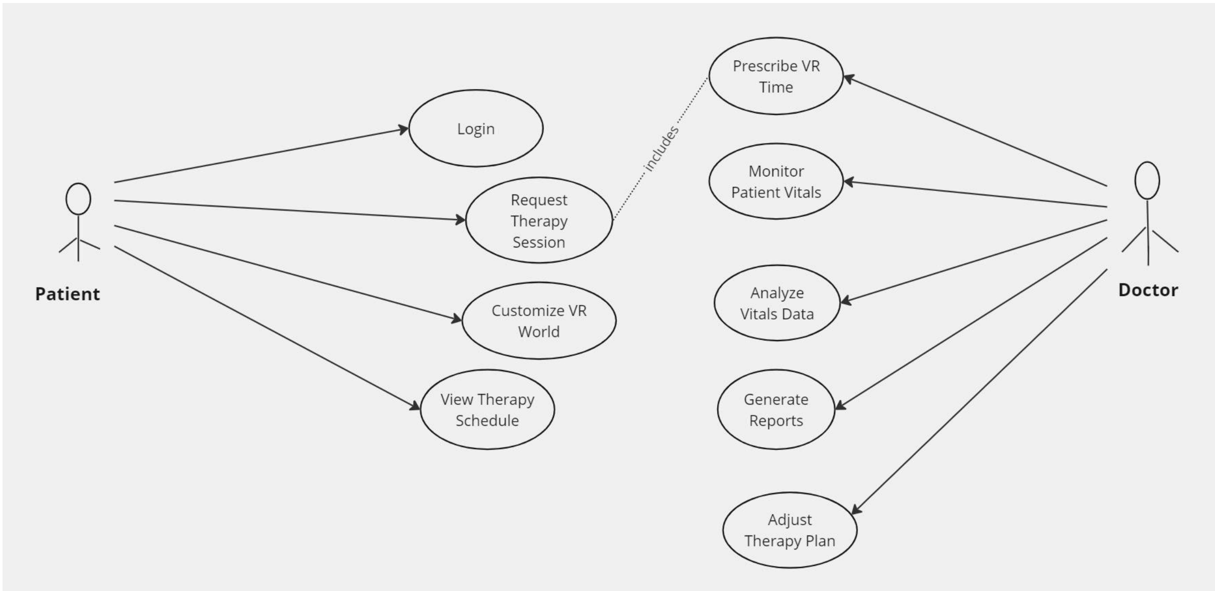


Fig 3.4.1 Use Case Diagram

The patient logs into the system and requests a VR therapy session. After the doctor prescribes the daily VR therapy time frame, the patient customizes their VR world and enters the VR therapy session using the prescribed time frame. During the session, the system monitors important patient vitals like heart rate and skin conductance to assess pain levels. The doctor analyzes the data collected, generates comprehensive session reports, and adjusts the therapy plan based on the insights. The patient can view their upcoming therapy schedule and the detailed session reports. Using the analytics and recommendations provided, the patient can better manage their phantom limb pain with effective VR therapy sessions designed by their doctor.

Workflow of the Use-Case diagram:

1. Patient Journey:

- Login: The patient logs into the system through a secure login portal to access their VR therapy sessions.
- Request Therapy Session: After logging in, the patient requests a VR therapy session by entering their doctor's ID.

- Customize VR World: The patient customizes their VR world, selecting a theme and describing the severity of their pain. This information helps the doctor tailor the therapy session.
- View Therapy Schedule: The patient can view their upcoming therapy schedule to know the prescribed therapy times.

2. Doctor's Role:
- Prescribe VR Time: The doctor prescribes a daily VR therapy time frame based on the patient's needs and pain severity.
- Monitor Patient Vitals: During the VR session, the doctor monitors key patient vitals, such as heart rate and skin conductance, to assess pain levels.
- Analyze Vitals Data: The doctor analyzes the collected vitals data to gain insights into the patient's pain levels and therapy effectiveness.
- Generate Reports: The system generates comprehensive session reports, providing analytics and insights on patient vitals and therapy performance.
- Adjust Therapy Plan: Based on the reports and insights obtained, the doctor adjusts the therapy plan, ensuring personalized and effective VR therapy.

3. Therapy Session Workflow:
- The patient enters the VR therapy session using the prescribed time frame.
- During the session, the system monitors vitals like heart rate and skin conductance levels to assess the patient's pain levels.
- The doctor analyzes this data to generate detailed reports and provides recommendations for future therapy sessions.

4. Reports and Recommendations:
- Obtain Inferences: The doctor reviews the analytics and inferences to understand the effectiveness of the therapy sessions.
- Analytics and Future Recommendations: Using the reports, the doctor provides personalized recommendations to the patient for better managing their phantom limb pain.

Chapter 4

ANALYSIS MODELING

4.1 Data Modeling

In this virtual reality (VR) project aimed at managing phantom limb pain (PLP), data modeling plays a crucial role in structuring and organizing the data collected from patients, doctors, and VR sessions. The conceptual data model defines key entities such as patients, doctors, VR sessions, VR themes, and psychological data, ensuring that the relationships between these entities are clear and meaningful. By designing a well-structured data model, we can efficiently track patient preferences and pain severity, analyze physiological data to identify pain patterns, and provide doctors with comprehensive reports to personalize VR therapy sessions. This structured approach enables seamless integration of patient data, VR themes, and session feedback to create a more effective and immersive therapeutic experience.

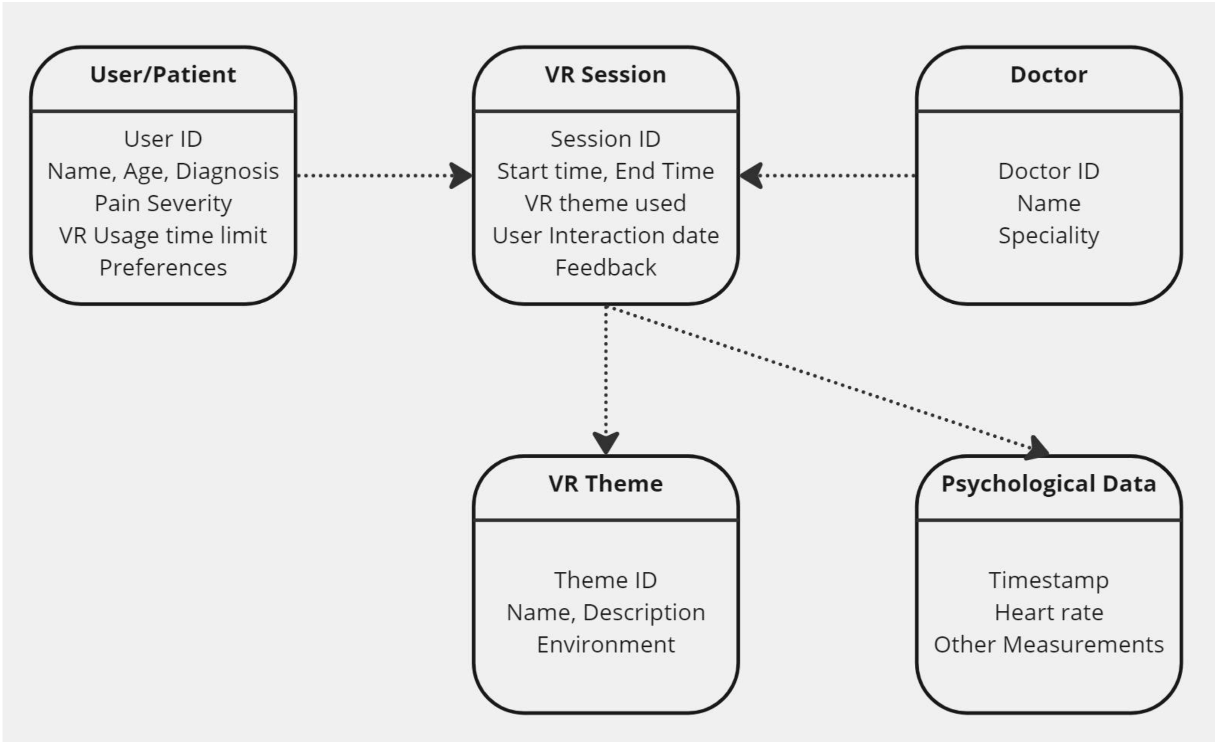


Fig 4.1.1 Data Modelling Diagram

I] User/Patient Entity

The User/Patient entity holds crucial information about each patient undergoing VR therapy. Attributes include the `User ID`, which uniquely identifies each patient, and `Name`, `Age`, and `Diagnosis` to offer personalized care. `Pain Severity` helps assess the level of phantom limb pain, while `VR Usage Time Limit` and `Preferences` guide therapy customization. For instance, preferences could include specific VR themes that patients find effective or enjoyable, ensuring sessions are tailored to their needs.

II] Doctor Entity

The Doctor entity represents the healthcare professionals overseeing VR therapy. It includes a `Doctor ID` for unique identification, along with `Name` and `Speciality` to denote the doctor's area of expertise. Speciality allows doctors to tailor their therapeutic recommendations and analyze patient data more effectively. They receive comprehensive reports after each VR session to adjust future treatment plans.

III] VR Session Entity

The VR Session entity tracks each therapeutic session, with a `Session ID` uniquely identifying it. `Start Time` and `End Time` mark the duration, while `VR Theme Used` links to the selected virtual environment. `User Interaction Data` records patient actions during the session, and `Feedback` captures the patient's experience, helping doctors refine and personalize future therapy.

IV] VR Theme Entity

The VR Theme entity defines the virtual environments available for therapy. Each theme is identified by a unique `Theme ID`, with attributes like `Name`, `Description`, and `Environment`. The `Description` provides details about the theme's purpose, and `Environment` indicates the virtual setting, such as a beach or pirate ship. These themes immerse patients in therapeutic activities, providing doctors with diverse options to customize sessions.

V] Psychological Data Entity

The Psychological Data entity captures real-time physiological measurements during each VR session. `Timestamp` records when each measurement was taken, while `Heart Rate` and `Other Measurements` (like skin conductance) monitor the patient's physiological responses. This data, linked to the VR sessions, helps doctors analyze patterns in patient reactions and refine therapy plans for improved outcomes.

4.2 Activity Diagrams / Class Diagrams

The class diagram in the "VR Phantom Haven" project illustrates the management of Phantom Limb Pain (PLP) using Virtual Reality (VR). It shows how patients and doctors interact through secure login portals to request and schedule VR therapy sessions. The diagram depicts the customization of a VR theme, the prescription of therapy timeframes, and the collection of physiological data, all culminating in analytics and future treatment recommendations by doctors.

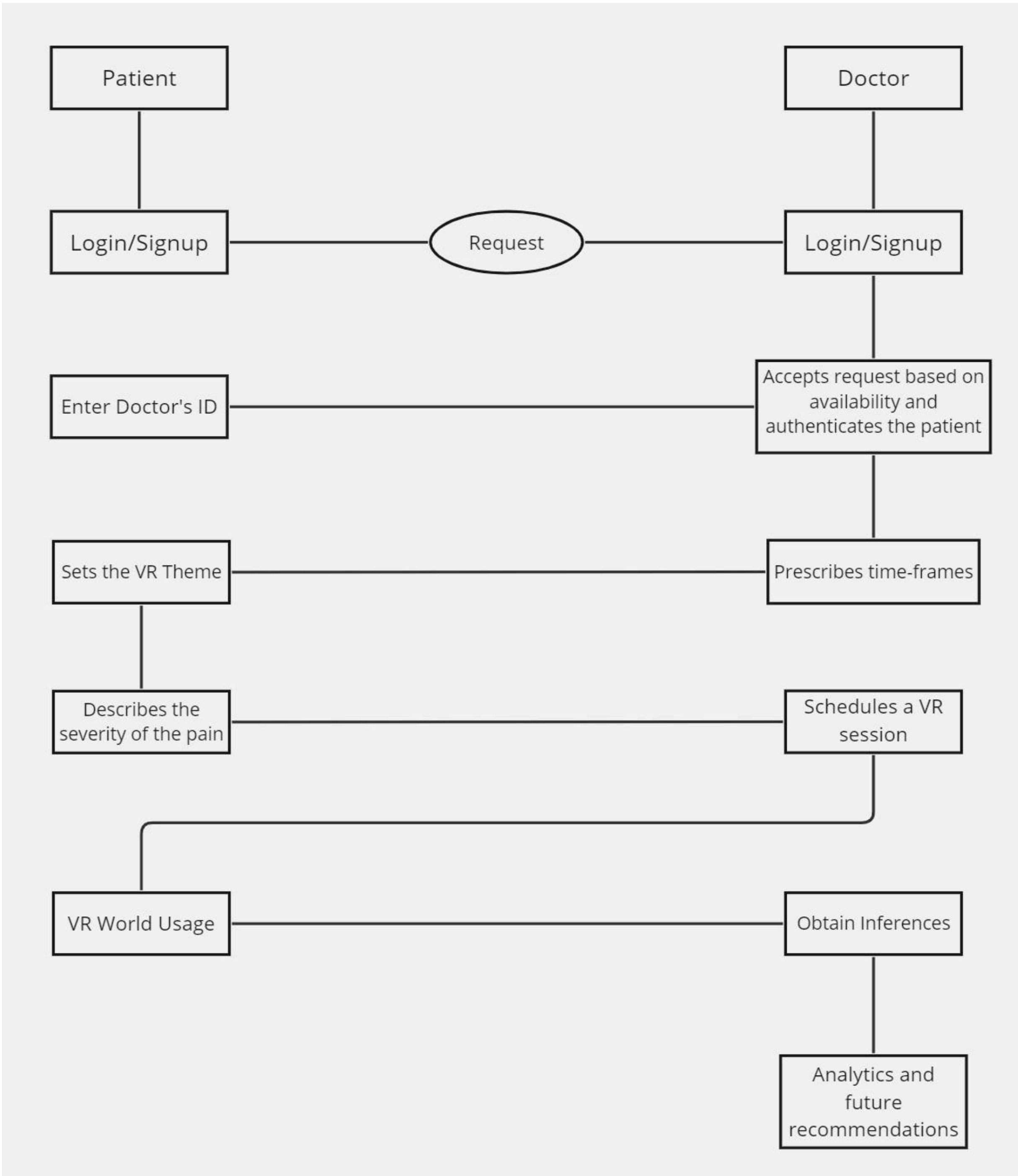


Fig 4.2.1 Activity Diagram

The class diagram provided illustrates the architecture of the VR Phantom Haven system, highlighting interactions between patients, doctors, and the VR system. Here's a step-by-step explanation:

1. Login/Signup:
   - Patients and doctors access the system through secure login/signup processes.
   - Doctors authenticate patients after verifying availability.

2. Request:
   - Patients initiate a VR therapy request by entering their doctor's ID.
   - Doctors approve requests based on availability and set treatment timeframes.

3. VR Theme Setup:
   - Patients customize their VR experience by selecting a VR theme.
   - They also describe their pain severity, providing doctors with crucial data.

4. Session Scheduling:
   - Doctors prescribe therapy timeframes and schedule a VR session.

5. VR World Usage:
   - Patients use VR headsets to immerse themselves in a tailored VR world.
   - Patient pain levels and physiological parameters are collected via an Apple Watch.

6. Inferences and Analytics:
   - Doctors analyze VR session data to obtain inferences.
   - They use this data to generate future treatment recommendations.

4.3 Functional Modeling

Functional modeling utilizes use case diagrams and system sequence diagrams to represent the interaction between users and the system functions in the "VR Phantom Haven" project. Key functions include:

1. Manage User Profiles: Functions that allow patients and doctors to update their information or preferences. Patients can adjust their VR therapy profiles, while doctors can authenticate patients and manage therapy requests.

2. Conduct Therapy Session: Detailed processes to handle the setup, execution, and teardown of VR therapy sessions. This includes patient login, theme selection, session scheduling, and session customization.

3. Monitor and Adjust Therapy: Functions to analyze incoming physiological data in real-time (via Apple Watch) and dynamically adjust therapy parameters based on predefined machine learning algorithms. It ensures personalized and effective pain management.

4. Generate Reports: Automated processes compile session data into comprehensive reports for review by the therapist. Reports include analytics on patient pain levels, session performance, and treatment recommendations.

5. Analytics and Recommendations: Post-session analysis is conducted to derive insights from the reports, allowing doctors to make future therapy recommendations and further personalize VR treatment plans.

4.4 TimeLine Chart

The timeline chart for the development and deployment of the VR system might include phases such as:

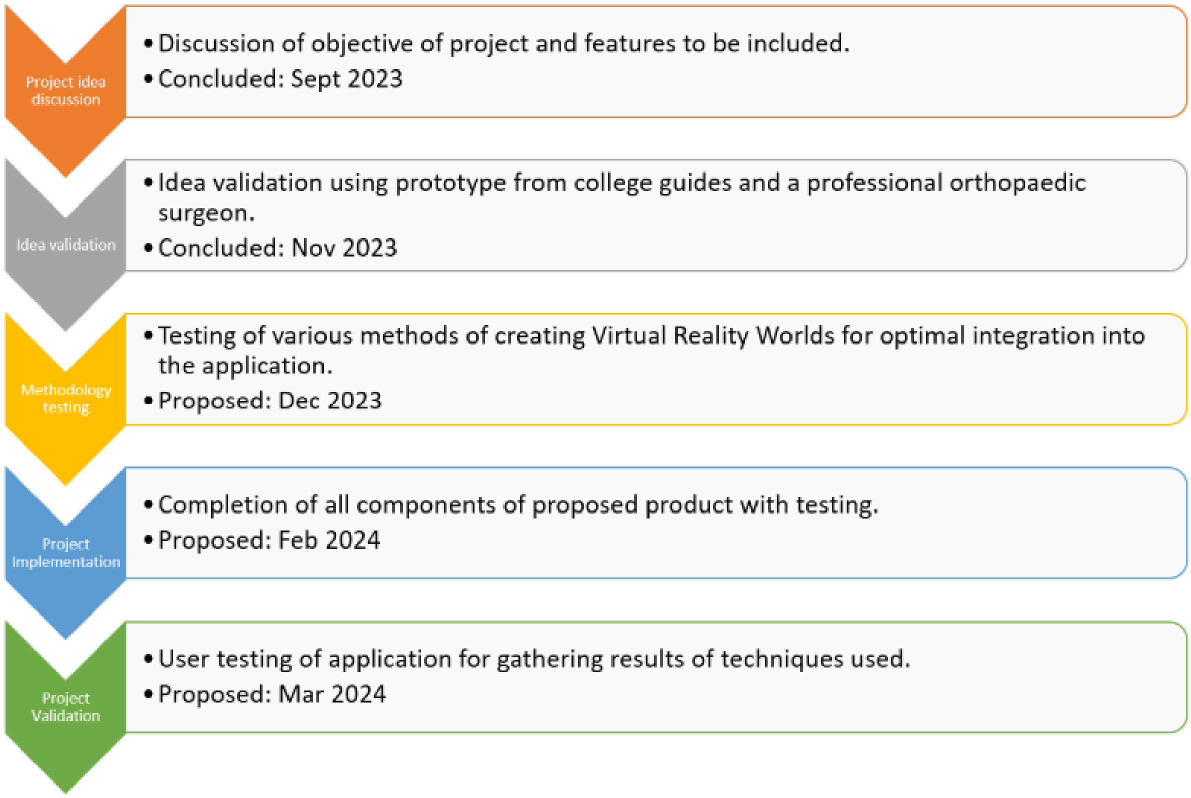


Fig 4.4.1 TimeLine Chart

- Prototype Development: Initial development phase focusing on core functionalities like user authentication, basic VR environment setup, and simple data capture.

- Alpha Testing: Internal testing phase with simulated data to ensure basic functionalities are working as intended.

- Beta Testing: Limited release to select patients and therapists to gather feedback and identify bugs.

- Launch: Full deployment of the system, followed by ongoing maintenance and updates based on user feedback and technological advancements.

Chapter 5

DESIGN

5.1 Architectural Design

The architectural design of the virtual reality healthcare system for amputee patients encompasses three key sections, each playing a crucial role in delivering personalized and effective therapy sessions. The Virtual Environment section serves as the immersive platform where patients engage in therapy, providing entry details such as personal information and selected VR themes, along with functionalities for real-time communication and structural movement simulation. The central Database section acts as the repository for patient records and session data, capturing vital information ranging from patient details to pain assessments. Its functions include updating patient information and monitoring the patient's VR experience for ongoing adjustments. On the right, the Doctor section provides healthcare professionals with access to patient details, past medical history, and current pain severity assessments, enabling them to prescribe personalized treatment plans tailored to individual progress and requirements. This architectural design facilitates seamless interaction between patients, their virtual environments, and healthcare providers, forming a comprehensive ecosystem aimed at optimizing PLP management outcomes.

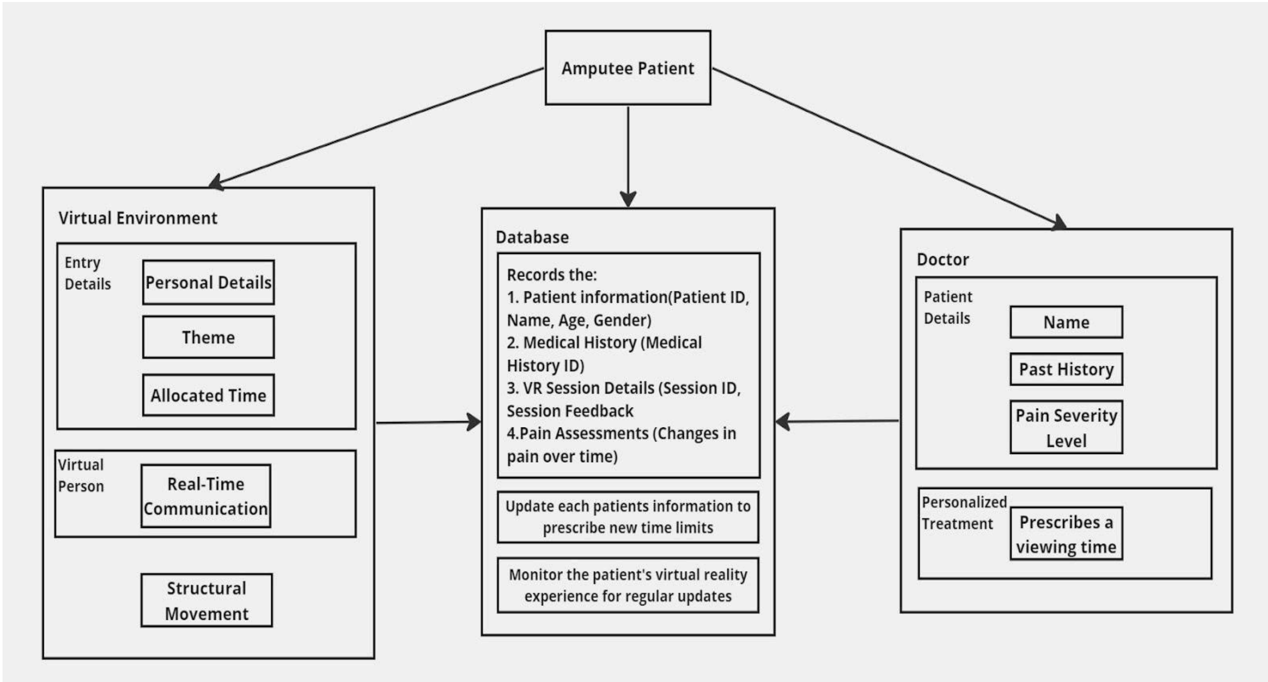


Fig 5.1.1 Architecture Diagram

The diagram illustrates the structure of a virtual reality healthcare system for amputee patients. It has three main sections:

1. Virtual Environment (Left)
   - Entry Details:
     - Personal Details: Information about the patient, such as name, age, and gender.
     - Theme: The selected VR environment for the therapy session.
     - Allocated Time: Time allocated for the VR session.
   - Virtual Person:
     - Real-Time Communication: Allows the patient to interact with the virtual environment.
     - Structural Movement: Simulates the movement of the virtual limbs or environment.

2. Database (Center)
   - Records the following information:
     1. Patient Information: Patient ID, Name, Age, and Gender.
     2. Medical History: Medical History ID.
     3. VR Session Details: Session ID, Session Feedback.
     4. Pain Assessments: Changes in pain levels over time.
   - Functions:

- Update patient information to prescribe new time limits.
- Monitor the patient's virtual reality experience for regular updates.

3. Doctor (Right)
   - Patient Details:
     - Name: Patient name.
     - Past History: Previous medical history.
     - Pain Severity Level: Current pain level assessment.
   - Personalized Treatment:
     - Prescribe a viewing time based on the patient's progress and requirements.

5.2 User Interface Design

The user interface design for the virtual reality healthcare system offers a seamless and intuitive experience for both doctors and patients, facilitating efficient navigation and access to relevant functionalities. Upon accessing the welcome page, users are presented with the option to log in as either a doctor or a patient, directing them to their respective portals tailored to their roles and requirements. For patients, the portal displays essential information such as the remaining prescribed usage time and a direct link to access the virtual world for therapy sessions. Meanwhile, the doctor portal provides an overview of all patients under their care, enabling quick access to individual patient details for comprehensive management. Within the patient details page, doctors can access detailed information about the patient's profile, ongoing medications, and key metrics to assess the efficacy of VR therapy, empowering them to make informed decisions regarding treatment adjustments. Through thoughtful interface design, the system aims to streamline user interactions, enhance usability, and ultimately improve the overall experience and effectiveness of PLP management.

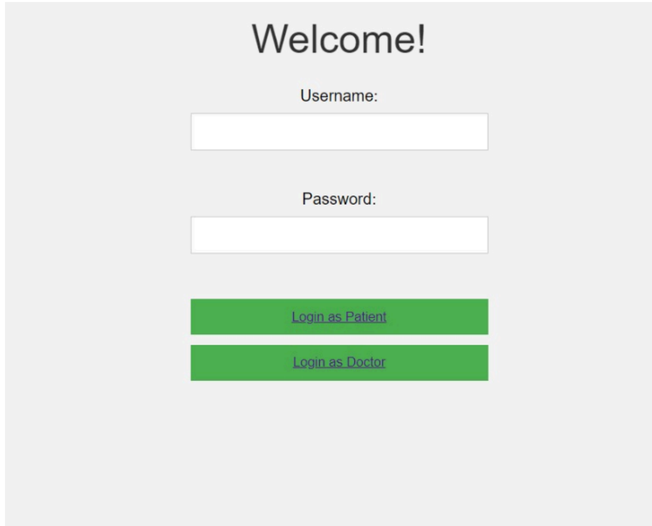


Fig 5.2.1 Welcome Page

The welcome page of the user interface gives an option to enter as a doctor or as a patient. Both these logins lead to their respective portals as seen in the following images.

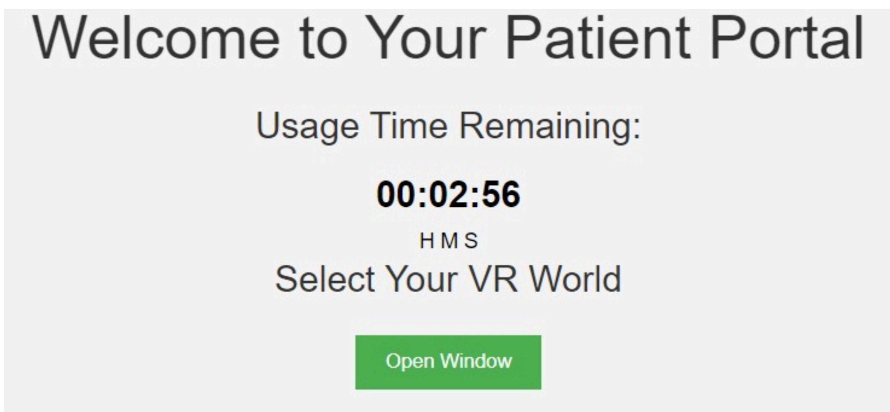


Fig 5.2.2 Patient Portal

Above is the patient portal which shows the remaining prescribed usage time for the patient and provides a link to open the virtual world. This page comes as after the user signs in as the patient.

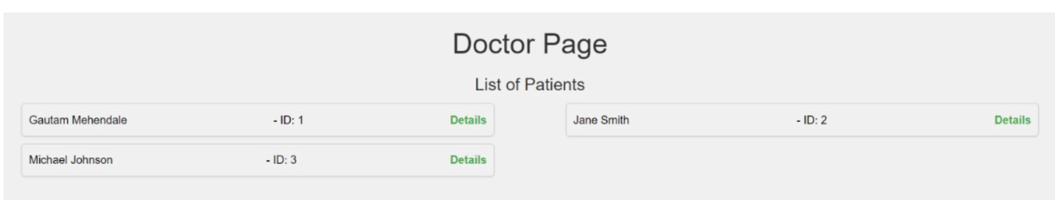
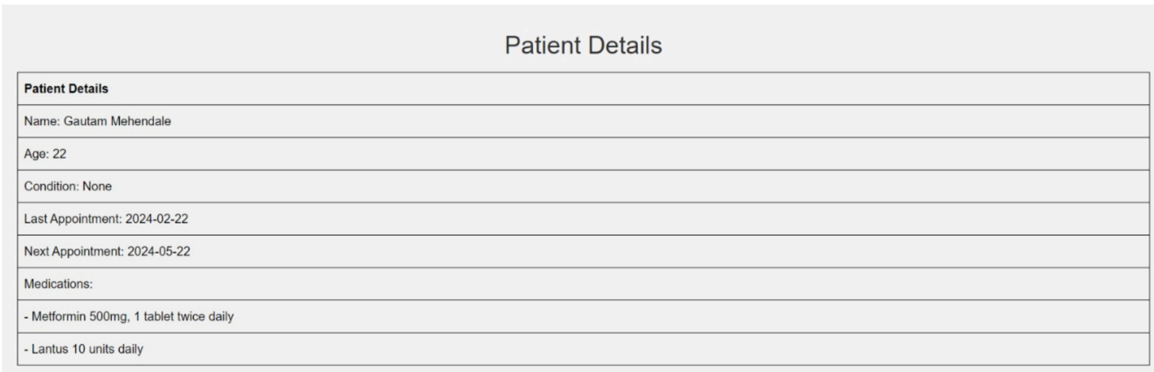


Fig 5.2.3 Doctor Portal

Above seen is the doctor portal. This portal is seen after the user signs in as the doctor. The doctor can see an overview of each of the patients taking a treatment under him and can go ahead and go to the patients' details page from here.



Patient Details

Patient Details
Name: Gautam Mehendale
Age: 22
Condition: None
Last Appointment: 2024-02-22
Next Appointment: 2024-05-22
Medications:
- Metformin 500mg, 1 tablet twice daily
- Lantus 10 units daily

Fig 5.2.4 Patient Details Page Part 1

Above seen is the top half of the patients' details page which illustrates the details about the patients and their ongoing medications.

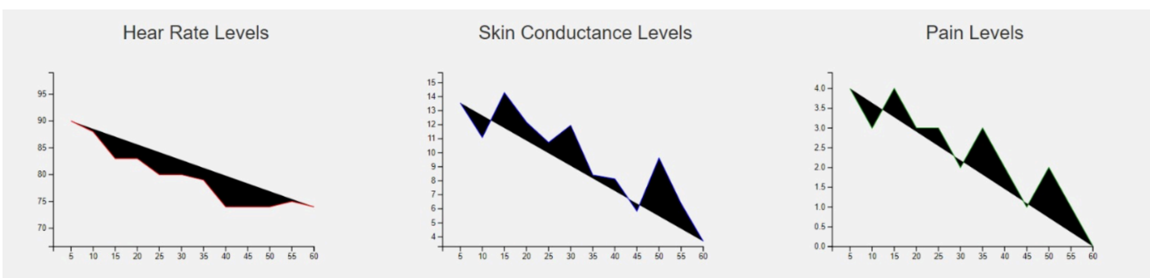


Fig 5.2.5 Patient Details Page Part 2

Above is the next half of the patients' details page. This illustrates the important metrics for the doctor to analyze the efficacy of the VR methodology used to treat the patient and if any further changes need to be made to the prescribed timings of the user or not.

Chapter 6

IMPLEMENTATION

6.1 Algorithms / Methods Used

The implementation of advanced algorithms and methods serves as the backbone of the proposed solution for managing Phantom Limb Pain (PLP). These algorithms are meticulously designed to leverage cutting-edge technologies and methodologies to address the multifaceted nature of PLP and provide personalized therapeutic interventions. The utilization of machine learning techniques for pain detection represents a cornerstone of the project, enabling the system to analyze biometric data collected from wearable devices and extract features indicative of pain levels. By employing supervised machine learning algorithms, such as Neural Networks, the system can classify pain levels based on these extracted features, thereby facilitating real-time analysis and adjustment of the virtual reality (VR) environment according to the user's current pain level. Additionally, the implementation of real-time data processing algorithms enables continuous monitoring and analysis of incoming physiological data, empowering the system to dynamically adapt the VR environment to optimize pain management outcomes. These sophisticated algorithms not only enhance the system's ability to detect and respond to changes in pain levels but also contribute to the creation of an adaptive VR environment that caters to individual preferences and therapy requirements, ultimately providing a tailored and effective therapeutic experience for PLP sufferers.

Machine Learning for Pain Detection

- Feature Extraction: The system uses biometric data collected through devices like an Apple Watch to extract features indicative of pain levels. Features might include heart rate variability, skin conductance, and motion data.
- Classification Algorithms: Employed supervised machine learning techniques, (Neural Networks), to classify the pain levels from the extracted features. These models are trained on a dataset comprising labelled examples of different pain states.
- Real-Time Analysis: Implement real-time data processing algorithms to analyse the incoming physiological data continuously. This enables the system to adjust the VR environment dynamically based on the user’s current pain level.

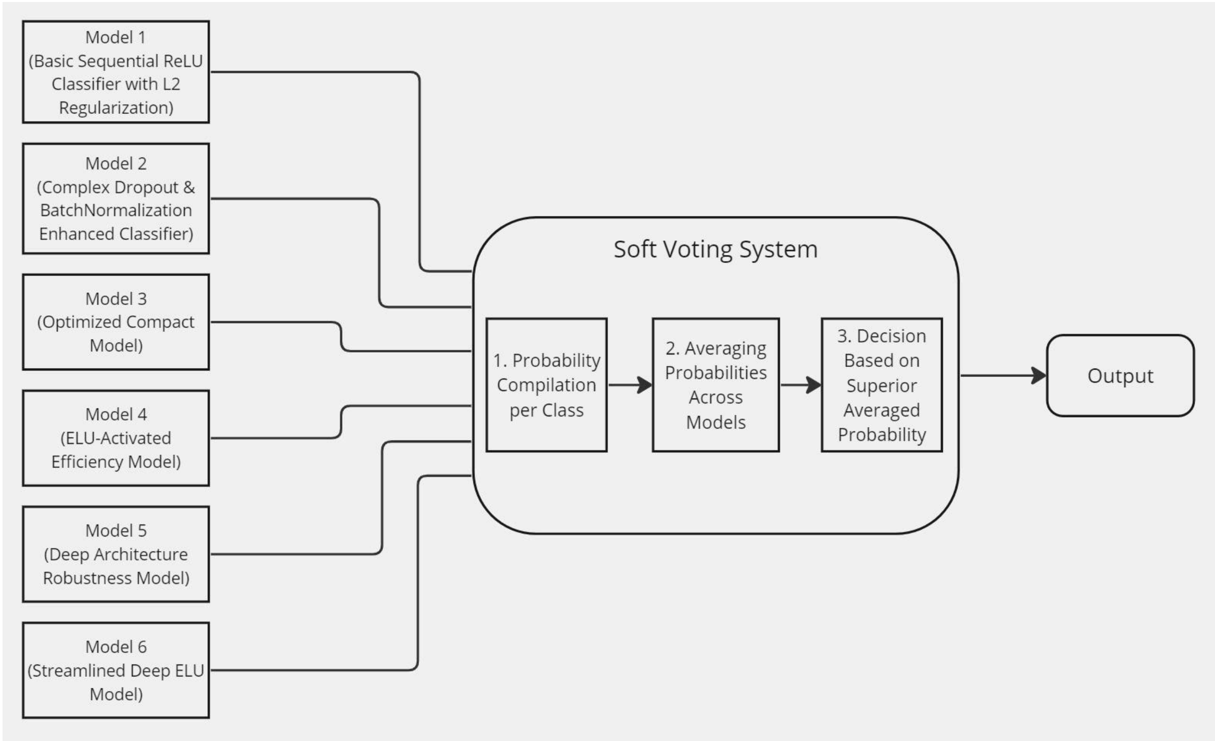


Fig 6.1.1 Deep Learning Architecture

Adaptive VR Environment

- Environmental Customization Algorithm: Use an algorithm that adjusts the VR environment based on user preferences and therapy requirements, such as changing scenarios, sounds, and interactive elements to enhance engagement and effectiveness.

- Feedback Loop: Incorporate a feedback system where the application adjusts in real-time based on the user’s interactions and the effectiveness of the pain management, ensuring a tailored therapeutic experience.

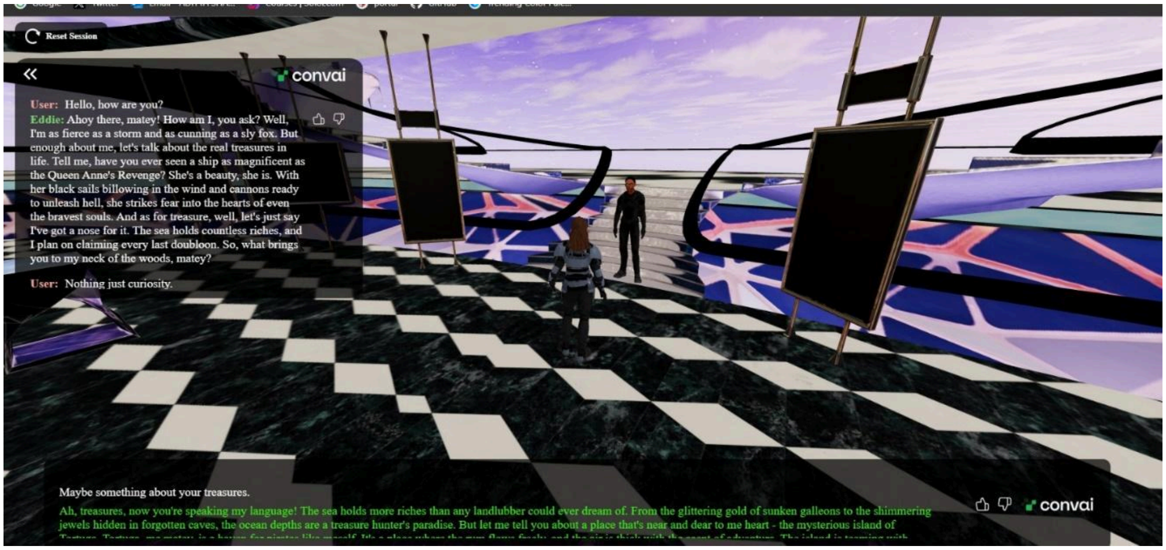


Fig 6.1.2 VR World

6.2 Working of the Project

The project operates on a comprehensive framework designed to seamlessly integrate advanced technologies and methodologies in order to deliver personalized and effective pain management solutions for amputee patients. Beginning with a secure login and authentication process, users gain access to a tailored VR therapy environment, marking the initial step towards immersive and targeted treatment. Once initiated, the system operates in real-time, continuously collecting physiological data through wearable devices and dynamically adjusting the VR environment to suit the patient's evolving needs. Throughout the session, therapists maintain remote oversight, enabling them to intervene or modify settings as required based on real-time data insights. At the session's conclusion, automated reporting mechanisms generate detailed summaries for therapist review, facilitating informed adjustments to the therapy plan for subsequent sessions. Safety protocols are embedded within the system to ensure patient well-being, with emergency mechanisms in place to terminate sessions in response to extreme physiological responses. This operational framework is supported by a robust technology stack, incorporating advanced VR development platforms and machine learning libraries, alongside compatible hardware to deliver an immersive and data-driven therapeutic experience. Through this holistic approach, the project aims to revolutionize PLP management by harnessing the power of technology and personalized care.

System Architecture

- Login and User Authentication: Users (patients and therapists) start by logging into the system, ensuring secure access to personalized therapy settings.
- Session Initiation: Once authenticated, the patient can initiate a VR session. The system loads the personalized environment settings based on previous sessions or therapist recommendations.

Real-Time Operation

- Data Collection: During the session, physiological data is continuously collected via wearable technology. This data is crucial for monitoring the patient’s response to the therapy.
- Dynamic Environment Adjustment: Based on the real-time data analysis, the VR environment adapts to the patient's needs. For instance, if increased stress levels are detected, the system might introduce more calming elements into the VR scenario.
- Therapist Monitoring and Intervention: Therapists can monitor sessions remotely in real-time. They have the capability to adjust settings or intervene if the data indicates that the current session setup is not effective.

Feedback and Reporting

- End-of-Session Summary: At the conclusion of a VR session, the system automatically generates a report detailing the session duration, changes in pain levels, patient engagement, and physiological data trends.
- Therapist Review and Adjustments: Therapists review these reports to assess the effectiveness of the session and make necessary adjustments to the therapy plan for future sessions.

Emergency Protocols

- Safety Mechanisms: The system includes safety protocols that automatically end the session if extreme physiological responses are detected, safeguarding the patient’s well-being.

Technology Stack

- Software: Utilize robust VR development platforms such as Unity or Unreal Engine integrated with machine learning libraries like TensorFlow or PyTorch for real-time data processing.

- Hardware: Depends on advanced VR headsets compatible with biometric sensors for an immersive experience and accurate data collection.

Chapter 7

TESTING

7.1 Test Cases

Functional Test Cases:

1. Login Functionality
   - Objective: Ensure that both patients and therapists can log in and log out successfully.
   - Test Steps:
     - Enter valid username and password.
     - Attempt to log in with invalid credentials.
     - Check response to a forgotten password.
   - Expected Result: Successful login with valid credentials; appropriate error messages for invalid attempts.

2. VR Environment Initialization
   - Objective: Verify that the VR environment initializes correctly with user-specific settings.
   - Test Steps:
     - Start a session and select a pre-defined environment.
     - Modify environment settings and start a new session.
   - Expected Result: The environment loads correctly with all settings applied.

3. Real-Time Pain Level Detection
   - Objective: Test the accuracy and responsiveness of the pain detection algorithm.
   - Test Steps:
     - Simulate different physiological inputs to represent varying pain levels.
   - Expected Result: The system correctly identifies and logs the pain level.

4. Session Adaptability

- Objective: Confirm that the VR system adapts in real-time to changes in detected pain levels.
- Test Steps:
  - Change pain level indicators during an active session.
  - Observe adjustments in the VR environment.
- Expected Result: Immediate and appropriate adjustments to the environment.

5. Emergency Protocol Activation
- Objective: Ensure the emergency shutdown activates under critical conditions.
- Test Steps:
  - Trigger an emergency scenario via the simulator.
- Expected Result: The system safely shuts down and logs the incident.

Non-Functional Test Cases:
1. Performance
- Objective: Evaluate the system's performance under typical and peak load conditions.
- Test Steps:
  - Conduct stress testing by simulating the maximum number of concurrent users.
- Expected Result: The system maintains functionality without significant performance degradation.

2. Usability
- Objective: Assess the ease of use and navigability of the VR interface for patients with varying degrees of technological proficiency.
- Test Steps:
  - Have users with different tech skills perform common tasks within the system.
- Expected Result: Users are able to navigate and use the system with minimal assistance.

7.2 Type of Testing Used

Unit Testing
- Purpose: Validate each individual component or module, such as login modules, data processing algorithms, and VR environment settings, for correctness in isolation.

Integration Testing

- Purpose: Ensure that different system modules work together seamlessly. This might include testing the integration between the user interface, backend algorithms, and data storage systems.

System Testing

- Purpose: Conduct comprehensive testing of the entire system to verify that it meets all specified requirements. This includes both hardware and software components of the VR system.

Acceptance Testing

- Purpose: Performed with real users to ensure the system meets their needs and performs satisfactorily in real-world scenarios. This would typically be done in a controlled clinical setting.

Stress Testing

- Purpose: Determine the robustness of the system under extreme conditions, such as handling an unusually high number of users or processing large volumes of data simultaneously.

Usability Testing

- Purpose: Specifically important for VR applications, this testing ensures that users can interact with the system effectively and without physical discomfort.

Chapter 8

Results and Discussions

The results of this research provide compelling evidence for the efficacy of the VR-based Phantom Limb Pain (PLP) management system. The machine learning models used to detect pain levels demonstrated remarkable accuracy and precision. Six different deep learning architectures were evaluated, with individual models achieving an average accuracy of 86% and precision of 89%. The implementation of an ensemble voting system, which weighted each model's precision on the validation set, further improved these metrics. The ensemble system reached an overall accuracy of 92% and a precision of 94%, signifying a significant improvement in pain level classification compared to individual models.

Results:

1. Deep Learning Model Performances:

Models	Accuracy	Precision
Model 1	83.4%	82.6%
Model 2	81.8%	83.8%
Model 3	80.9%	**89%**
Model 4	**86%**	80.6%
Model 5	85.5%	82.5%
Model 6	81.4%	84.4%

Tab 8.1 Deep Learning Model Results

- Ensemble Voting System:
  - Overall accuracy of 92% and precision of 94%.

2. Pilot Study Results:

- Patient 1: Pain level reduced from 3 to 0 after 30 minutes of VR therapy.
- Patient 2: Pain level reduced from 4 to 2 after 45 minutes of VR therapy.
- Patient 3: Pain level reduced from 3 to 1 after 35 minutes of VR therapy.

3. Explainable AI Analysis:

- SHAP (SHapley Additive exPlanations) was used to identify impactful features.
- Heart rate variability and skin conductance were the most significant indicators of pain levels.

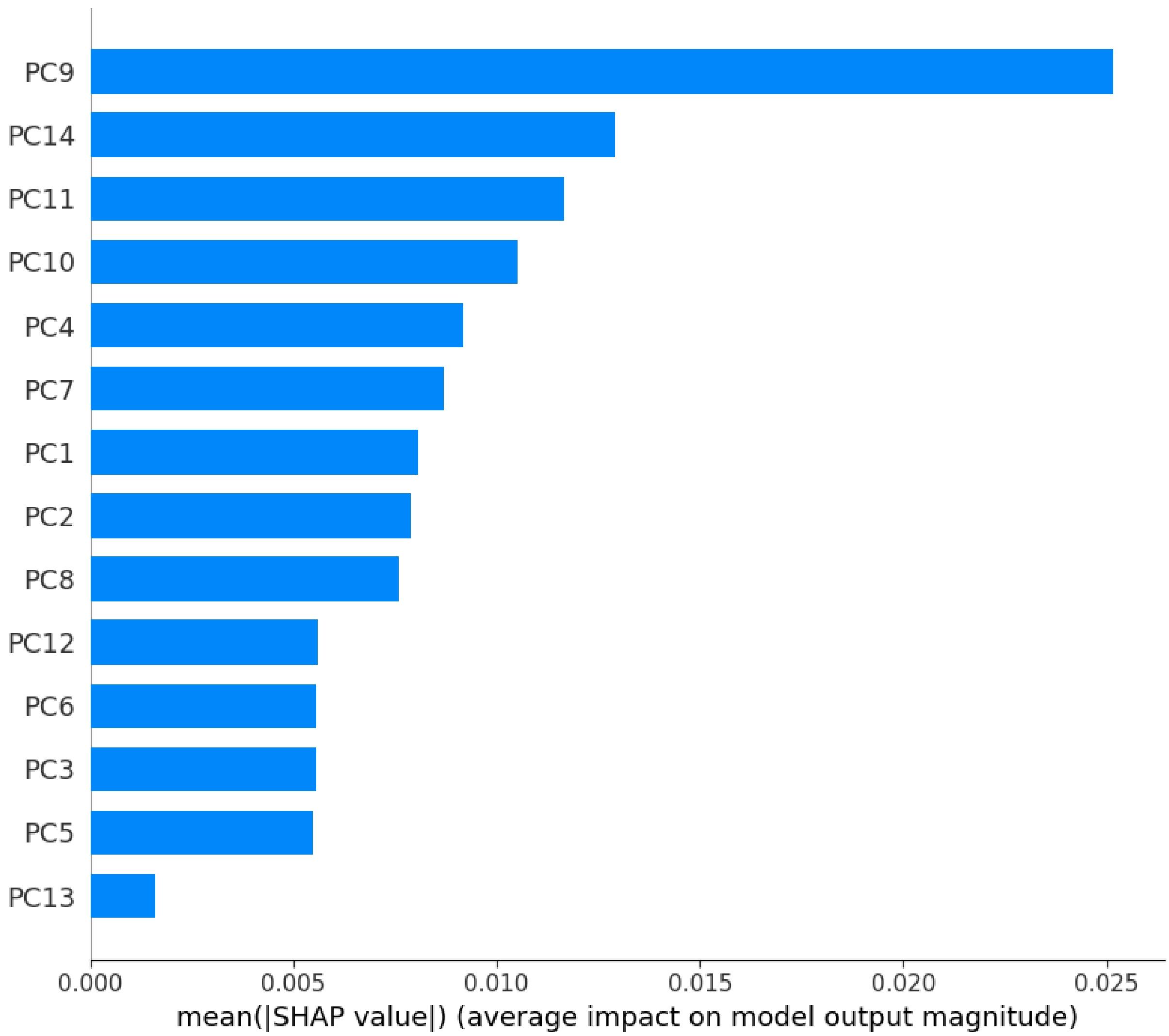


Fig 8.1 SHAP Summary Plot

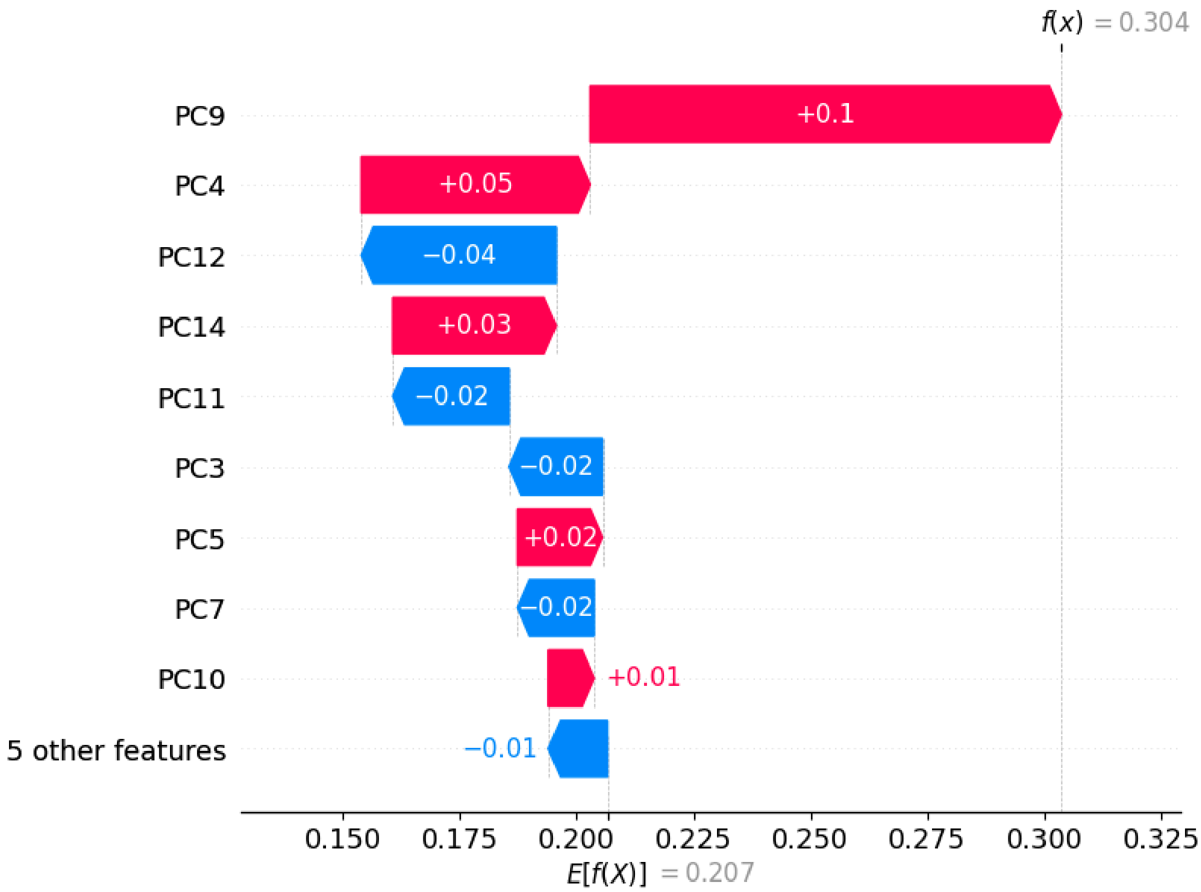


Fig 8.2 SHAP Waterfall Plot

Fig 8.3 Feature Loading of Principal Components

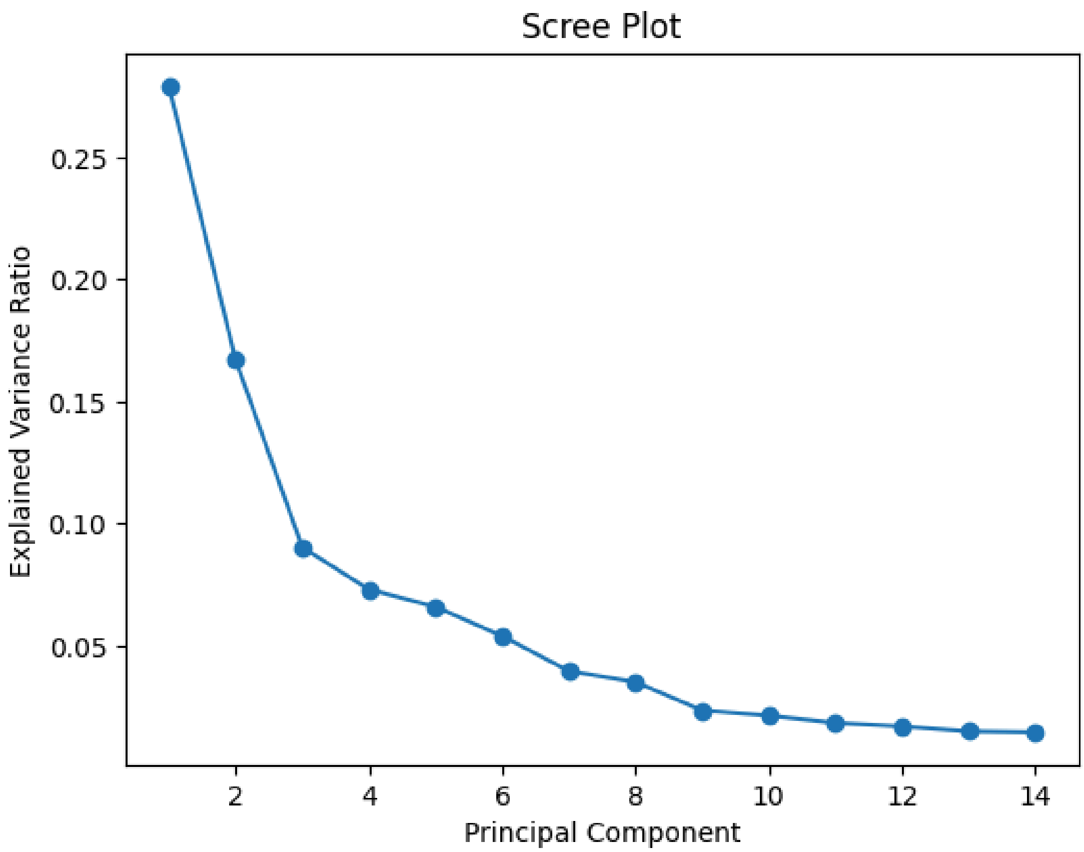


Fig 8.4 Scree Plot

4. VR Therapy Feedback:

- All three patients reported significant decreases in pain intensity within an average of 30-45 minutes.
- The immersive pirate-themed environment effectively distracted patients from sensations of phantom pain.

Discussion:

The findings from this study indicate that the VR-based Phantom Limb Pain (PLP) management system presents a promising solution for alleviating phantom limb pain through immersive virtual reality experiences. The machine learning models demonstrated impressive accuracy and precision in detecting pain levels, with an ensemble voting system achieving 92% accuracy and 94% precision. The pilot study further validated the efficacy of the system, as all three participants experienced significant pain reduction from level 3 to level 0 within 30 to 45 minutes of VR exposure.

The personalized therapeutic approach enabled by real-time physiological monitoring and therapist-controlled protocols proved highly effective. The pirate-themed immersive environment and interactive features created a compelling distraction, breaking the cycle of chronic pain and anxiety commonly associated with PLP. By engaging patients in visually stimulating and interactive activities, the VR therapy likely stimulated neuroplasticity, helping the brain remap the somatosensory cortex and reduce phantom limb sensations.

The SHAP analysis highlighted heart rate variability and skin conductance as the most significant physiological indicators of pain levels, underscoring the importance of continuous physiological monitoring in managing chronic pain. The adaptability of the VR environment, combined with therapist-controlled protocols, facilitated a personalized therapy approach that could be tailored to each patient's unique needs and preferences.

Despite these promising findings, the study was limited by the small sample size of the pilot group. While all three participants experienced significant pain reduction, larger clinical trials involving more diverse participant groups are needed to confirm these results and establish the long-term efficacy of the VR therapy. Additionally, the study focused primarily on short-term pain reduction, leaving room for future research to investigate the sustained effects of VR therapy on PLP over longer periods.

Key Discussion Points:

1. Effectiveness of Machine Learning Models:

- The high accuracy and precision of the machine learning models demonstrated their potential for accurately classifying pain levels based on physiological data.
- The ensemble voting approach further improved classification performance, emphasizing the value of leveraging multiple models.

2. Efficacy of VR Therapy:

- The pilot study results indicate that VR therapy can lead to significant pain reduction in a short period, supporting previous findings on the effectiveness of virtual reality for pain management.
- The pirate-themed environment and interactive features helped create a compelling distraction from the sensations of phantom pain.

3. Personalized Therapeutic Approach:

- The system's adaptability to individual patient needs and preferences, facilitated by real-time monitoring and customization, enabled a personalized therapy approach.
- The combination of interactive interfaces, customizable environments, and real-time physiological monitoring allows therapists to tailor the therapy to each patient's requirements.

4. Potential Mechanisms of Action:

- VR therapy may stimulate neuroplasticity, helping the brain remap the somatosensory cortex and reduce phantom limb sensations.
- The immersive environment and engaging activities provided a distraction that helped break the cycle of chronic pain and anxiety often associated with PLP.

5. Limitations and Future Research:

- Sample Size: The pilot study included only three participants, limiting the generalizability of the findings. Larger clinical trials are necessary to confirm the efficacy of this approach.
- Longitudinal Effects: The study focused on short-term pain reduction. Future research should investigate the long-term effects of VR therapy on PLP.
- Broader Applicability: The system could be tested with a broader range of chronic pain conditions, such as neuropathic pain and post-surgical rehabilitation, to assess its generalizability.

Chapter 9

CONCLUSIONS & FUTURE SCOPE

The VR-based PLP management system, incorporating real-time pain detection via machine learning (92% accuracy, 94% precision), yielded promising results in a pilot test. All three patients experienced significant pain reduction (level 3 to 0) within 30-45 minutes of VR exposure. While limited by sample size, this study suggests VR offers a safe, engaging, and potentially effective approach to PLP management. Further research with larger groups is needed to confirm these findings and explore VR's impact on psychological well-being. This work contributes to the advancement of VR technology for pain management and improving quality of life for amputees.

The future scope of research for the VR-based Phantom Limb Pain (PLP) management system is promising and multifaceted. Firstly, extending its applications to broader chronic pain management, such as neuropathic pain and post-surgical rehabilitation, could significantly amplify its impact, offering alternatives to traditional pain management methods. Technological enhancements also hold substantial promise; integrating emerging technologies like augmented reality (AR) and utilizing advanced AI algorithms could dramatically improve the personalization and effectiveness of therapies. Furthermore, conducting longitudinal clinical trials would provide deeper insights into the long-term efficacy of VR therapy across diverse patient demographics. Collaborative interdisciplinary research involving neuroscientists could elucidate the neuroplastic changes induced by VR, enhancing our understanding of its mechanisms. Additionally, exploring the psychological and social outcomes of such innovative treatments could provide a holistic view of its benefits and limitations, paving the way for more comprehensive care solutions in chronic pain management.

Appendix

Detailed information, lengthy derivations, raw experimental observations etc. are to be presented in the separate appendices, which shall be numbered in Roman Capitals (e.g. "Appendix I"). You can include the standard algorithms that are part of the project's concept and which are not already explained in the report.

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Publications

Articles, technical notes etc. on the topic of the report published by the candidate may be separately listed after the literature cited. This may also be included in the contents. The candidates may also include reprints of his/her publications after the literature citation.

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