International Journal for Multidisciplinary Research (IJFMR)
E-ISSN: 2582-2160 ● Website: www.ijfmr.com ● Email: editor@ijfmr.com

Adaptive Movement Analysis and Enhanced Self-Monitoring Hypercube for Parkinson's Disease

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Abstract
Parkinson's Disease (PD) is a chronic neurodegenerative disorder characterized by motor impairments, including tremors, rigidity, bradykinesia, and postural instability, which progressively diminish patients' ability to perform daily activities independently. Current rehabilitation practices, primarily focused on physical therapy, medication, and traditional support devices, provide essential symptom management but often lack customization to individual patient needs, leading to inconsistent adherence and limited long-term benefits. This paper introduces the Adaptive Movement Analysis and Enhanced Self-Monitoring Hypercube, a novel rehabilitation framework aimed at improving PD management through a comprehensive, adaptive approach.The system leverages cutting-edge sensors, including the MPU6050 Inertial Measurement Unit (IMU) and infrared proximity sensors, integrated with a Teensy microcontroller to deliver real-time movement analysis and tailored exercise feedback. Through Bluetooth-enabled connectivity, patient data is transmitted to a digital platform where it can be analyzed and adjusted based on performance metrics. Additionally, gamification techniques, task-specific training modules, and customizable feedback mechanisms are embedded to increase patient engagement and adherence to exercise routines. This adaptive solution provides a structured, motivating environment that addresses the fluctuating capabilities of PD patients, promoting functional recovery and enhanced self-monitoring.Initial evaluations indicate that this technology-driven rehabilitation tool can improve motor control, optimize medication efficacy, and reduce disability levels, potentially transforming the traditional therapeutic landscape for PD. This paper elaborates on the system's architecture, the implementation of its functional components, and its potential to elevate the standard of PD care through personalized, accessible, and affordable rehabilitation solutions.

1 Introduction

Parkinson's Disease (PD) is a progressive neurodegenerative disorder marked by the degeneration of dopamine-producing neurons in the brain's substantia nigra, a region responsible for regulating smooth, controlled movements. As dopamine levels decrease, individuals experience a variety of motor symptoms, including tremors, muscle rigidity, slowness of movement (bradykinesia), and impaired balance. The precise cause of PD is not fully understood; however, it is believed to result from a combination of genetic predispositions and environmental factors. Primarily affecting adults over the age of 60, PD's incidence has also been noted in younger populations, making it a global health concern with significant personal and societal impact.

While there is no cure for PD, a range of treatment options—such as medications, physical therapy, and, in severe cases, surgery—help manage symptoms. Rehabilitation is integral to these efforts, as it targets symptom control and the preservation of independence. Comprehensive rehabilitation strategies encompass physical exercises, occupational therapy, speech therapy, and psychological support, aiming to enable individuals to perform daily activities with reduced dependence. However, traditional rehabilitation routines are often repetitive and can lead to low patient engagement, particularly given the chronic and progressive nature of the disease.

To optimize PD management, this paper explores a multifaceted approach, prioritizing goals such as enhancing patients' ability to complete daily tasks independently, minimizing disabilities associated with motor impairments, and optimizing medication effects with complementary therapies. By leveraging adaptive movement analysis and self-monitoring tools, this research aims to develop a customizable rehabilitation framework that integrates gamification, real-time feedback, and personalized exercise programs. This framework seeks to foster motivation, adherence, and measurable improvements in mobility and overall quality of life, aligning with patient needs across varying disease stages. The proposed solution is designed to address the growing need for accessible, engaging, and cost-effective rehabilitation methods for PD patients, contributing to a more dynamic approach to symptom management.

2 Objectives

The objectives of Parkinson's disease management encompass a multifaceted approach aimed at optimizing patients' functionality and quality of life:

1. **Maintaining Functionality:** This objective focuses on preserving and enhancing patients' ability to perform daily activities independently. By implementing targeted exercises and interventions, the goal is to mitigate the impact of motor impairments on activities of daily living, such as dressing, eating, and personal hygiene. Through tailored rehabilitation strategies, individuals with Parkinson's disease can maintain a sense of autonomy and self-sufficiency in their daily routines.
2. **Improving their ability to perform daily activities:** This objective emphasizes the importance of rehabilitation techniques and assistive devices in improving patients' functional capacity. By addressing specific motor deficits through physical therapy, occupational therapy, and speech therapy, individuals with Parkinson's disease can regain lost skills, adapt to new challenges, and optimize their independence in performing essential tasks.
3. **Minimizing Disability:** The objective of minimizing disability revolves around mitigating the impact of motor impairments on patients' overall quality of life. By employing a comprehensive approach that encompasses medical management, rehabilitation interventions, and psychosocial support, the aim is to reduce the burden of disability associated with Parkinson's disease. Strategies may include mobility aids, adaptive 4 equipment, and environmental modifications to facilitate participation in meaningful activities and promote social engagement.
4. **Minimizing disabilities associated with motor impairments:** This objective focuses on addressing the specific motor symptoms of Parkinson's disease, such as tremors, rigidity, bradykinesia, and postural instability. Through a combination of pharmacological interventions and nonpharmacological therapies, including exercise, deep brain stimulation, and speech therapy, the goal is to minimize functional limitations and optimize patients' mobility and motor control.

5. **Optimizing Medication Effects:** This objective centers on maximizing the efficacy of pharmacological treatments in managing motor symptoms and enhancing patients' overall well-being. Additionally, complementary therapies such as physical activity, nutrition, and stress management may augment the effects of medication, further improving motor function and quality of life.

3 Existing Solutions

1.TITLE: Cognitive rehabilitation in Parkinson's disease: a systematic review AUTHOR: Hamad Alzahrani, Annalena Venneri
DATE OF PUBLICATION: February, 2018
Background:
Cognitive impairments are the most common non-motor symptoms in Parkinson's disease (PD). These symptoms have a negative impact on patients' quality of life and daily living activities. This review will focus on published articles that investigated the efficacy of cognitive rehabilitation in PD.
Objectives:
To review the existing literature on the efficacy of cognitive rehabilitation in PD and highlight the most effective form of intervention to prevent cognitive decline. This review will also point out any limitations and provide directions for future research. Methods:
Published articles available in the Web of Science and PubMed databases up to November 2017 were reviewed for possible inclusion. We identified 15 articles that examined the effects of cognitive rehabilitation in PD and met inclusion criteria.
2.TITLE: Virtual reality in physical rehabilitation of patients with Parkinson's disease AUTHOR: Gisele de Paula Vieira, Daniela Freitas Guerra Henriques de Araujo, Marco Antonio Araujo Leite, Marco Orsini, Clynton Lourenço Correa
DATE OF PUBLICATION: June 2014
Background:
The Virtual Reality (VR) can be a therapeutic tool used in neurorehabilitation field. It is considered a ludic activity that provides visual and auditory feedbacks, facilitating the patients' adherence to treatment.
Objectives: To perform literature review about influences of VR in rehabilitation of patients with Parkinson's disease.
Methods:
Data banks were used from the following virtual libraries: Medline, PEDro, Lilacs, Scielo and PubMed using the following keywords: Parkinson's disease and Virtual Reality; Parkinson's disease and Wii as well as analogous keywords in Spanish and Portuguese to obtain the scientific papers. PEDro scale was used to analyze the methodological quality of the papers.
3.TITLE: In-patient multidisciplinary rehabilitation for Parkinson's disease: a randomized controlled trial.
AUTHOR: Marco Monticone, Emilia Ambrosini, Alessandro Laurini, Barbara Rocca, Calogero Foti.
DATE OF PUBLICATION: December 2015
Background :
This study was undertaken to evaluate the effects of an inpatient 2- month multidisciplinary rehabilitative program of task-oriented exercises, cognitive– behavioral training, and occupational therapy on motor impairment, activities of daily living, and quality of life (QoL) in subjects with long-duration Parkinson's disease (PD).
Methods:

Subjects were randomly selected for an experimental (multidisciplinary rehabilitative care) and a control group (general physiotherapy) and were assessed before treatment, after 8 weeks (post- treatment), and 12 months after the end of treatment. Medications were not adjusted during training.

Results:

Outcome measures were the Movement Disorder Society Unified Parkinson's Disease Rating Scale, Part III (primary outcome), the Berg Balance Scale, the Functional Independence Measure, and the 39-Parkinson's Disease Questionnaire. A linear mixed model for repeated measures was used for each outcome.

4. TITLE: New sensor and wearable technologies to aid in the diagnosis and treatment monitoring of Parkinson's disease

AUTHOR: Mariana HG Monje, Guglielmo Foffani, José Obeso, Álvaro Sánchez-Ferro

DATE OF PUBLICATION: Jan, 2019

Background:

Parkinson's disease (PD) is a degenerative disorder of the brain characterized by the impairment of the nigrostriatal system. This impairment leads to specific motor manifestations (i.e., bradykinesia, tremor, and rigidity) that are assessed through clinical examination, scales, and patient reported outcomes. New sensor-based and wearable technologies are progressively revolutionizing PD care by objectively measuring these manifestations and improving PD diagnosis and treatment monitoring. However, their use is still limited in clinical practice.

5. TITLE: Smart gait-aid glasses for Parkinson's disease patients AUTHOR: DaeHan Ahn, Hyerim Chung, Ho-Won Lee, Kyunghun Kang, Pan-Woo Ko, Nam Sung Kim, Taejoon Park DATE OF PUBLICATION: 2017

Background:

Parkinson's disease (PD) is a chronic progressive disease caused by loss of dopaminergic neurons in the substantia nigra, degenerating the nervous system of a patient over time. Freezing of gait (FOG), which is a form of akinesia, is a symptom of PD. Meanwhile, recent studies show that the gait of PD patients experiencing FOG can be significantly improved by providing the regular visual or auditory patterns for the patients. In this paper, we propose a gait-aid system built upon smart glasses.

RESULT:

Our system continuously monitors the gait and so on of a PD patient to detect FOG, and upon detection of FOG it projects visual patterns on the glasses as if the patterns were actually on the floor. Conducting experiments involving ten PD patients, we demonstrate that our system achieves the accuracy of 92.86% in detecting FOG episodes and that it improves the gait speed and stride length of PD patients by 15.3 ~ 37.2% and 18.7 ~ 31.7%, respectively.

4 Proposed Solution

The proposed solution integrates innovative strategies to enhance rehabilitation outcomes for patients with Parkinson's Disease. By addressing key challenges identified in traditional rehabilitation approaches, the framework aims to foster greater engagement, improve functionality, and ultimately enhance the quality of life for individuals with PD.

1. Motivation and Engagement

Problem: Traditional rehabilitation exercises can be repetitive, tedious, and lead to low adherence among patients, resulting in suboptimal outcomes.

Solution: Implementing gamification principles significantly enhances engagement and motivation. By incorporating game mechanics such as points, levels, challenges, and rewards, patients are incentivized to actively participate in their rehabilitation exercises. This approach transforms monotonous tasks into engaging activities, fostering a sense of accomplishment and increasing adherence to prescribed regimens.

2. Task-Specific Training

Problem: Traditional exercises often fail to translate effectively into functional tasks that patients encounter in their daily lives.

Solution: Game-based training can mimic real-world activities, providing targeted practice that enhances functional abilities. By creating scenarios that reflect daily tasks, patients can develop skills in a context that directly applies to their lives, making rehabilitation more relevant and effective.

3. Feedback and Performance Monitoring

Problem: A lack of consistent feedback and difficulties in objectively monitoring progress can hinder patient motivation and overall progress in rehabilitation.

Solution: Gamified interventions provide real-time, interactive feedback based on performance, enabling patients to track their progress and adjust their efforts accordingly. This immediate feedback loop not only boosts motivation but also allows for personalized adjustments to training protocols, enhancing overall efficacy.

4. Customization and Adaptability

Problem: Static exercise routines may not cater to individual differences in disease severity, progression, and patient preferences.

Solution: The proposed gamified system will include dynamic adjustments to game difficulty and tasks based on real-time user performance. This adaptability ensures that each patient receives a challenge appropriate to their current abilities, promoting continuous improvement and preventing frustration or disengagement.

5. Social Interaction and Support

Problem: The lack of social interaction and support can negatively impact motivation and overall rehabilitation outcomes.

Solution: Incorporating multiplayer or collaborative game features can foster social interaction among patients. This community-building aspect not only enhances motivation but also provides emotional support, creating a sense of belonging and shared experience in the rehabilitation journey.

6. Accessibility and Affordability

Problem: Traditional rehabilitation equipment can be expensive and often inaccessible to a significant portion of the patient population.

Solution: By integrating the gamified rehabilitation program with widely available devices such as smartphones or gaming consoles, the proposed solution can significantly improve accessibility and affordability. This approach reduces barriers to entry, allowing more individuals to benefit from the rehabilitation process.

7. Ethical Considerations

Problem: An over-reliance on gamification might overshadow clinical recommendations and potentially lead to unrealistic expectations regarding rehabilitation outcomes.

Solution: To mitigate these concerns, the development of gamified interventions will be done in collaboration with healthcare professionals. This partnership ensures that the games align with clinical goals and prioritize user safety and well-being. Furthermore, clear guidelines and educational resources will be provided to set realistic expectations for patients and caregivers regarding the rehabilitation process.

5 Implementation

A. Prototype Development

1. **System Architecture** The implementation of the Adaptive Movement Analysis system is built around a modular architecture, combining various sensors and a central microcontroller to create a responsive rehabilitation platform for individuals with Parkinson's disease. The primary components of this system include the **MPU6050 Inertial Measurement Unit**, **IR Sensor**, **Rotary Encoder**, and a **Teensy microcontroller**. Each component plays a crucial role in capturing movement data, enabling real-time analysis and feedback to enhance rehabilitation exercises.
2. **Sensor Integration**

a. **MPU6050 (Inertial Measurement Unit)**: The MPU6050 consists of a three-axis gyroscope and a three-axis accelerometer. Its integration involves connecting the sensor to the Teensy microcontroller via the I2C protocol. Calibration is performed at startup to ensure accurate orientation and acceleration readings. The MPU6050 is critical for assessing hand movement during rehabilitation, capturing both the angle and speed of the user's motions.

b. **IR Sensor**: The IR sensor is employed to detect the proximity of the user's finger to specific target objects during exercises. This sensor aids in ensuring proper positioning and engagement during rehabilitation tasks. It is connected to the Teensy board, where the input data is processed to determine whether the user is correctly aligned with the exercise target.

c. **Rotary Encoder**: The rotary encoder is used to measure finger flexion and extension angles. By tracking these movements, the system can provide insights into the user's performance and progress in hand exercises. This encoder is integrated into the system via GPIO pins on the Teensy, allowing real-time monitoring of finger positions.

3. **Microcontroller (Teensy Board) Setup**

a. **Teensy Board Configuration**: The Teensy board, specifically the Teensy 4.0 model, serves as the system's brain, processing data from the sensors and managing user interactions. It requires a stable power supply, typically from a USB connection or a dedicated battery. The programming environment used for this project is the Arduino IDE, where relevant libraries such as Wire.h for I2C communication and Encoder.h for rotary encoder integration are utilized.

b. **Data Processing**: The Teensy processes the incoming data from the sensors to calculate key performance indicators such as movement angles, speed, and distance. Algorithms implemented in the software analyze these data points, allowing the system to track progress in real-time and adjust exercise protocols as necessary.

c. **Control Logic**: The control logic embedded in the Teensy governs how the rehabilitation exercises are administered. It dynamically adjusts exercise intensity based on user performance, ensuring that the challenges remain appropriate and beneficial as the user progresses through their rehabilitation journey.

4. **User Interface Development**

a. **Visual Feedback Mechanism**: The user interface is designed to provide immediate visual feedback on exercise performance. An OLED display connected to the Teensy shows real-time data such as the number of repetitions completed, angles of finger movements, and other relevant metrics. This instant feedback helps motivate users and allows them to track their progress visually.

b. Mobile Application Integration: For enhanced user experience, a mobile application can be integrated to provide remote access to performance data and exercise recommendations. Technologies like React Native can be utilized to develop this application, which communicates with the Teensy via Bluetooth. This connectivity allows users to receive notifications about their performance and reminders for rehabilitation exercises.

5. Data Recording and Analysis

a. Data Storage: Data collected from the sensors is crucial for tracking user progress over time. The system can utilize an SD card module connected to the Teensy to log exercise performance data. This information can later be analyzed to determine trends in user improvement, providing valuable insights for both users and healthcare providers.

b. Performance Metrics: Key performance metrics tracked by the system include the accuracy of finger movements, the speed of execution, and the consistency of exercise performance. This data allows for tailored adjustments in rehabilitation protocols to maximize efficacy.

B. User Interaction

1. User Enrollment :The system begins with a user enrollment process, which includes an initial assessment to determine the user's capabilities and specific needs. During this phase, healthcare professionals can set customized rehabilitation plans tailored to the individual's current condition, taking into account factors such as disease stage and motor abilities.

2. Exercise Protocols

a. **Customizable Exercise Programs**: The system offers customizable exercise programs based on the user's initial assessment. Exercises may include finger extension and flexion tasks, coordination drills, and target-reaching activities. Each program is designed to address specific motor deficits associated with Parkinson's disease.

b. **Guidance During Exercises**: Users are guided through their exercises via the visual feedback provided on the OLED display, which prompts them to maintain proper form and alignment. Audio cues can also be incorporated to enhance guidance, particularly for users with visual impairments.

3. Real-time Interaction

a. **Feedback Mechanisms**: Users receive real-time feedback during their exercises, with auditory signals indicating correct or incorrect movements. This immediate response helps reinforce proper techniques and encourages adherence to the rehabilitation protocol.

b. **Progress Tracking**: Users have access to their progress through both the on-device display and the mobile application. Performance data, such as total repetitions and accuracy rates, are presented in an easily digestible format, allowing users to visualize their improvements over time.

4. Adaptability The system's adaptability is a key feature that tailors the rehabilitation experience to each user. Based on real-time performance data, the system can adjust the difficulty of exercises, ensuring that users are consistently challenged without feeling overwhelmed. This personalization fosters a sense of autonomy and encourages ongoing engagement in rehabilitation activities.

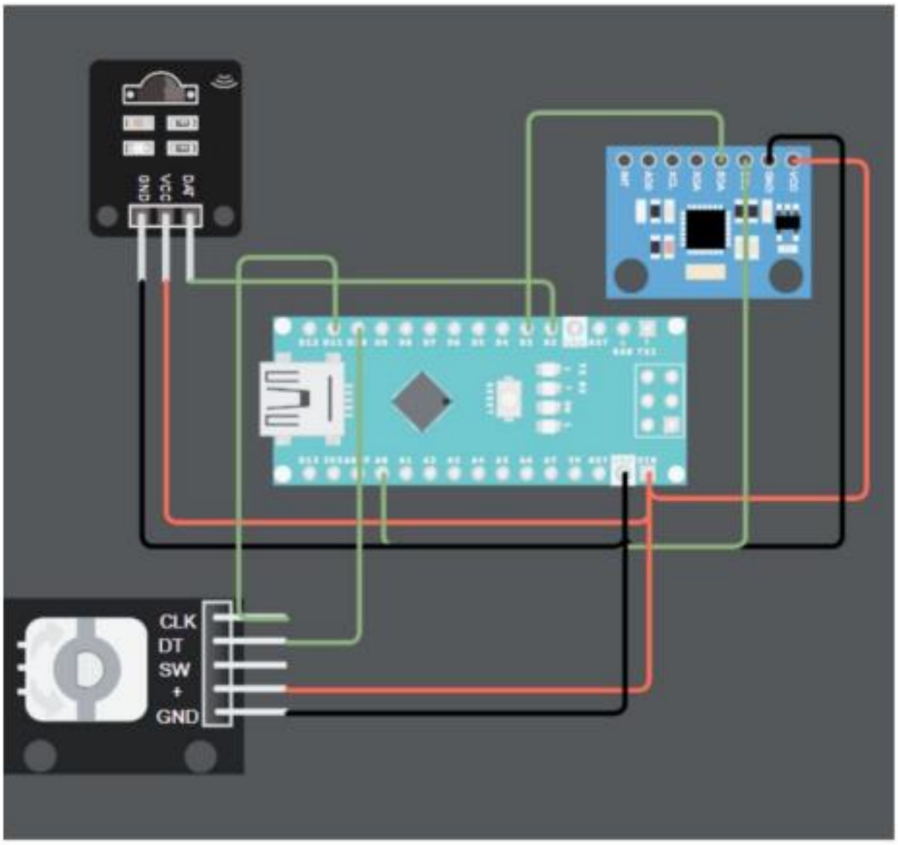
C. Feedback Mechanisms

1. **User Feedback Collection** Feedback from users is essential for the continuous improvement of the system. After each session, users can complete surveys or provide verbal feedback to capture their

experiences, challenges, and suggestions for enhancement.

2. **Monitoring User Engagement** Engagement levels are tracked through analytics built into the mobile application and the main system. Metrics such as session frequency, completion rates, and user satisfaction scores are collected and analyzed to assess how well the system meets users' needs.
3. **Iterative Improvement** The feedback collected from users and healthcare professionals is used to inform iterative improvements to the system. By collaborating with medical professionals, the project ensures that the system remains aligned with clinical best practices and effectively addresses the rehabilitation needs of individuals with Parkinson's disease.

D. Circuit Diagram



Inertial Measurement Unit (IMU) Sensor (MPU6050):

- **Function**: Measures orientation and acceleration.
- **Connections**:

a. Connect the MPU6050 to the microcontroller (Teensy) via I2C (SDA and SCL pins).
b. Ensure power connections are made (VCC and GND).

Bluetooth Module (HC-05 or HC-06):

- **Function**: Facilitates wireless communication.
- **Connections**:

a. Connect the Bluetooth module's TX to the RX pin of the Teensy and vice versa.
b. Connect the power and ground pins accordingly.

Teensy 4.0 Microcontroller:

- **Function**: Processes data from sensors and controls overall operations.
- **Connections**:

a. Connect the IMU and Bluetooth module as mentioned above.
b. Additional components (like sensors) should be connected to the appropriate GPIO pins.

IR Sensor:

- **Function**: Detects proximity of the finger during exercises.
- **Connections**:

a. Connect the output pin of the IR sensor to one of the analog input pins on the Teensy.
b. Power the sensor using appropriate voltage levels.

Rotary Encoder:

- **Function**: Tracks finger movement.
- **Connections**:

a. Connect the encoder pins to digital input pins on the Teensy for reading rotation.

E. Developed Model:

7 Conclusion

The Adaptive Movement Analysis and Enhanced Self-Monitoring Hypercube project aims to address the significant challenges faced by individuals with Parkinson's disease through innovative and tailored rehabilitation solutions. By focusing on maintaining functionality, improving daily activity performance, minimizing disabilities associated with motor impairments, and optimizing medication effects, this project strives to enhance the overall quality of life for patients.Through extensive stakeholder interactions, it became evident that a holistic approach, incorporating both physical rehabilitation exercises and technological innovations, is crucial in managing Parkinson's disease effectively. Our proposed solution leverages gamification and task-specific training to improve adherence to rehabilitation exercises, providing users with engaging and personalized experiences. Additionally, the integration of real-time feedback and performance monitoring will empower patients, encouraging them to actively participate in their rehabilitation journey.Moreover, this project emphasizes the importance of accessibility and affordability, ensuring that effective rehabilitation solutions reach a broader audience. By incorporating inexpensive and readily available technology, we aim to eliminate barriers to access while promoting social interaction and support among users.In conclusion, our project holds the potential to revolutionize the rehabilitation landscape for individuals with Parkinson's disease, fostering greater autonomy, enhanced quality of life, and a more comprehensive understanding of their condition. Moving forward, continuous collaboration with healthcare professionals and ongoing feedback from patients will be essential in refining our solution and ensuring its effectiveness in real-world applications.

8 Future Works

The development of the Adaptive Movement Analysis and Enhanced Self-Monitoring Hypercube is a significant step toward improving rehabilitation for individuals with Parkinson's disease. However, several avenues for future work can further enhance the project's impact and effectiveness:

1. Longitudinal Studies: Conducting longitudinal studies to assess the long-term effectiveness of the proposed system on patient outcomes will provide valuable insights. Tracking improvements in mobility, independence, and overall quality of life over extended periods will help validate the efficacy of our rehabilitation approach.
2. Integration of Advanced Technologies: Future iterations of the project could explore the integration of advanced technologies such as artificial intelligence and machine learning algorithms. These technologies could analyze movement data more comprehensively, providing personalized feedback and adaptive training protocols that evolve with the patient’s progress.
3. Expansion of Gamification Elements: While the initial gamification components have shown promise, further research can explore additional game mechanics that enhance user engagement and motivation. Incorporating elements like virtual reality or augmented reality could create immersive experiences, making rehabilitation more enjoyable and effective.
4. Collaboration with Healthcare Professionals: Strengthening partnerships with healthcare professionals and rehabilitation specialists will ensure that the project aligns with clinical guidelines and best practices. Their input can guide the development of training protocols and enhance the relevance of the system in real-world clinical settings.
5. Patient-Centered Design Iterations: Engaging patients and caregivers in the design process through focus groups and usability testing will be crucial for refining the system. Gathering feedback from end-users will help address specific needs, preferences, and challenges faced by individuals with Parkinson’s disease, ensuring the solution is user-friendly and effective.
6. Accessibility and Affordability Studies: Investigating cost-effective solutions and strategies to improve the accessibility of rehabilitation technologies will be essential. Collaborating with healthcare organizations to explore funding options and insurance coverage could facilitate wider adoption of the system.
7. Broader Application Across Neurological Disorders: Expanding the scope of the project to include other neurological disorders could provide insights into similar rehabilitation challenges faced by patients. Tailoring the system to accommodate various conditions will enhance its versatility and impact.

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