Haptic Feedback for Stroke Rehabilitation in Virtual Environment

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***Abstract*— Stroke is a leading cause of disability worldwide, often resulting in motor impairments. Traditional rehabilitation methods can be time-consuming and less engaging. This project introduces a novel stroke rehabilitation system that combines virtual reality (VR) with haptic feedback to provide an immersive and interactive therapeutic experience. By integrating a Meta Quest 2 headset with a custom-designed haptic glove, the system delivers precise tactile feedback, simulating real-world interactions within a virtual environment. This innovative approach aims to enhance patient engagement, motivation, and overall recovery outcomes, revolutionizing the field of stroke rehabilitation.**

Keywords*— *Virtual reality (VR), Meta Quest2, Haptic Feedback, Actuator, Driver, Stroke Patients, Rehabilitation

I. INTRODUCTION

Stroke is a leading cause of disability worldwide, often resulting in motor impairments that require extensive rehabilitation. Conventional stroke rehabilitation methods rely on repetitive physical exercises and require constant supervision by therapists, making them time-consuming, resource-intensive, and less engaging for patients. This project introduces a novel stroke rehabilitation system that combines haptic feedback with a virtual reality environment to provide a more immersive, interactive, and patient-friendly solution. Utilizing a custom-designed glove equipped with actuators, this system delivers precise tactile feedback to simulate real-world interactions, helping patients regain motor functions more effectively. By integrating advanced technology with therapeutic principles, the project aims to redefine the rehabilitation process, making it more accessible, efficient, and engaging for patients and therapists alike.

The system integrates a Meta Quest 2 headset with a wearable haptic glove and specialized controllers. The glove contains actuators for delivering precise haptic feedback. The haptic system enhances VR immersion by simulating realistic touch sensations. When users interact with virtual objects, they receive tactile feedback through the actuators, creating a lifelike experience. This setup provides more engaging and motivating therapy for stroke patients, aiding in their recovery by making exercises feel real, interactive, and enjoyable in a safe virtual environment. This project aims to achieve the following objectives for stroke rehabilitation:

A. Enhanced Therapy Engagement: Implementing touch feedback mechanisms within the VR application to deliver realistic tactile sensations that mimic therapeutic exercises. This significantly enhances patient engagement by creating an interactive and stimulating rehabilitation environment, encouraging consistent participation.

B. Facilitating Motor Skill Recovery: Integrating advanced haptic feedback technology to aid stroke patients in relearning fine and gross motor skills. By providing real-time tactile feedback during exercises, patients can develop better control, precision, and coordination of their movements.

C. Promoting Cognitive and Physical Connection: Providing physical feedback to reinforce the brain-body connection during therapy. The tactile sensations help patients better understand and refine their movements, improving their spatial awareness and fostering neuroplasticity for recovery.

D. Personalized and Adaptive Therapy: Enabling tailored rehabilitation experiences by adjusting haptic feedback intensity and patterns based on the patient’s progress and needs. This ensures that therapy sessions remain challenging yet achievable, promoting steady improvement over time.

By leveraging haptic feedback, this project aims to revolutionize stroke rehabilitation by creating an immersive, effective, and patient-centered VR therapy platform that accelerates recovery and enhances overall therapy outcomes.

II. PREVIOUS WORK

Global statistics in Fig. 1. reveal a significant burden of the condition, with 12.2 million new cases annually (incidence rate: 157.99 per 100,000) and over 101 million people currently affected (prevalence rate: 1,002.23 per 100,000). Women are more affected

(1,463.46 per 100,000) compared to men (1,160.44 per 100,000). Prevalence is lower in younger individuals (15-49 years: 578.56 per 100,000) and increases substantially in older populations. These figures highlight the urgent need for focused research and interventions. Global statistics reveal a significant burden of the condition, with 12.2 million new cases annually (incidence rate: 157.99 per 100,000) and over 101 million people currently affected (prevalence rate: 1,002.23 per 100,000). Women are more affected (1,463.46 per 100,000) compared to men (1,160.44 per 100,000). Prevalence is lower in younger individuals (15-49 years: 578.56 per 100,000) and increases substantially in older populations. These figures highlight the urgent need for focused research and interventions [1].

Measure: Incedence	Number	Crude rate per 100,000 per year (95% UI)*
Ages (all), Sexes (both)	12,224,551	157.99 (142.71-175.63)
15-49 years	1,978,946	50.29 (43.02-58.71)
<70 years	7,622,088	104.79 (92.54-119.06)
Men (all ages)	5,787,446	149.12 (134.95-166.31)
Women (all ages)	6,437,105	166.92 (150.75-185.90)
Measure: Prevalence	**Number**	**Crude rate per 100,000 per year (95% UI)***
Ages (all), Sexes (both)	101,474,558	(1,002.23-1,167.80)
15-49 years	22,766,796	578.56 (509.50- 654.80)
<70 years	68,406,930	940.46 (859.03-1,028.24)
Men (all ages)	45,036,191	1,160.44 (1,059.77- 1,269.34)
Women (all ages)	56,438,366	1,463.46 (1,347.19- 1,595.47)

Fig. 1. Statistics of Stroke globally

Existing treatments in stroke rehabilitation are,

A. Physical Therapy (PT): Focuses on improving motor skills, strength, and coordination through repetitive exercises. Techniques include walking aids, strength training, and task-specific training.

B. Occupational Therapy (OT): Helps patients regain skills needed for daily living and work activities. Includes strategies to compensate for motor or cognitive impairments.

C. Robot-Assisted Rehabilitation: Uses robotic devices to assist and provide feedback during repetitive exercises. Helps in precise motion control and extended therapy sessions.

D. Virtual Reality (VR) and Haptic Feedback: Provides an immersive environment for motor and cognitive training. Offers engaging, customizable therapy that promotes motivation and adherence.

Some of the challenges with existing methods in stroke rehabilitation is,

A. Limited Accessibility: Rehabilitation centers may not be accessible in remote or underdeveloped areas. Long wait times and limited therapy resources can delay recovery.

B. High Costs: Stroke rehabilitation, particularly advanced methods like robotics or VR, can be prohibitively expensive for many patients.

C. Adherence and Motivation: Patients often struggle with maintaining long-term motivation for therapy due to its repetitive and time-consuming nature.

D. Individual Variability: Stroke impacts differ greatly among individuals, requiring personalized rehabilitation plans. Some patients may show limited response to standard interventions.

E. Resource Constraints: Shortage of skilled therapists and rehabilitation technologies in many healthcare systems. Overburdened facilities in regions with high stroke prevalence.

F. Complexity of Neurological Recovery: Neural plasticity varies, and there is no "one-size-fits-all" approach. Recovery can be slow and plateau after a certain point.

III. Our Approach

In this project, we propose an innovative rehabilitation system combining haptic feedback and virtual reality (VR) to enhance stroke recovery. The solution features a custom-designed glove equipped with 40 actuators, controlled through a robust system architecture involving ESP32 microcontrollers, multiplexers, and haptic drivers (DRV2605L). This glove provides real-time tactile sensations that simulate real-world interactions, helping patients re-engage their motor skills.

The VR environment offers interactive games with varying difficulty levels, keeping patients motivated while targeting their affected motor skills. The system uses a TCP communication link between the Meta Quest VR headset and the actuator controller, ensuring precise and immersive haptic responses during gameplay.

Designed for in-home rehabilitation, the solution bridges the gap between traditional therapy and modern technology, providing an engaging, accessible, and effective way to support stroke recovery.

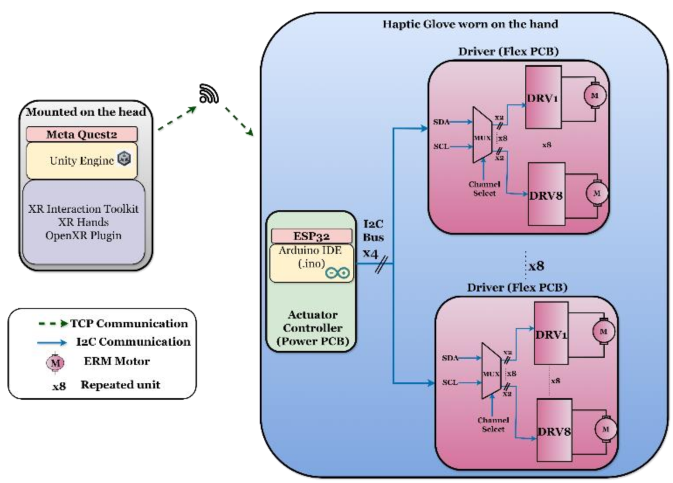

Fig. 2. System Design

As shown in Fig. 2. Our system has the below components,

A. The virtual environment is developed using Unity3D and XR Interaction Toolkit with precise joint tracking using XR Hands package.
B. Actuator controller consists of
(a) ESP32 microcontroller, programmed using Arduino IDE,
(b) 3.7V, 450mAh LiPo battery that powers the microcontroller for approximately 2.5 hours,
(c) 3.7V, 4000mAh LiPo battery supports the entire system of eight Flex PCBs for up to 2 hours when all motors are active.
C. Each of eight Flex PCBs house 8 DRV2605L haptic drivers and 8 ERM motors (total of 64 motors), delivering realistic touch sensations with adjustable intensities.
The software communication flow is,
A. VR Interaction to ESP32: User hand-tracking in the VR environment maps object interactions to specific actuator coordinates, sending data to ESP32 through TCP communication.
B. ESP32 to haptic hardware: The actuator controller processes coordinate and intensity data to determine which ERM motors to activate with their vibration strength.
C. Hardware Feedback: Drivers activate ERM motors, delivering precise real-time haptic feedback based on mapped intensity patterns.

The features that are included in this project are,

i. Simultaneous actuation
ii. Intensity Control
iii. Interactive therapy with easy, medium and hard levels
iv. Precise Feedback

With this the VR game developed keeps the patient engaged and motivated to finish the game which in turn mainly completes their exercise at home in their convenience.

Advantages of our solution are,

A. Haptics facilitates muscle memory, reinforcing correct motion patterns and improving coordination. This is especially useful in regaining hand and arm functionality, as the haptic feedback promotes precise movements and aids in recovering dexterity.
B. Haptic feedback reinforces the brain's awareness of physical actions, which is critical in improving sensory-motor integration. This can result in better motor control and faster recovery of lost skills.
C. The tactile sensations and feedback make exercises feel more engaging and realistic, which can increase the patient's willingness to participate in therapy. The interaction becomes a more enjoyable and goal-oriented activity, which helps keep them committed to the rehabilitation process.
D. Through virtual reality (VR) combined with haptics, patients can practice tasks in a simulated environment without physical risks. This setup allows them to experiment and improve without the fear of falling or causing strain, making rehabilitation safer.
E. In home therapy.

IV. HARDWARE COMPONENTS

A. ERM motor: ERMs in Haptics can be added to anything that you touch or touches you. ERM has traditionally been a popular choice for haptic feedback due to its simplicity and lower cost compared to newer technologies [2]. This likely contributes to its large market share. The market trends suggest a gradual shift towards more advanced and efficient technologies like Piezoelectric and EAP, but ERM maintains a significant presence, particularly in applications where cost-effectiveness and reliability are critical.

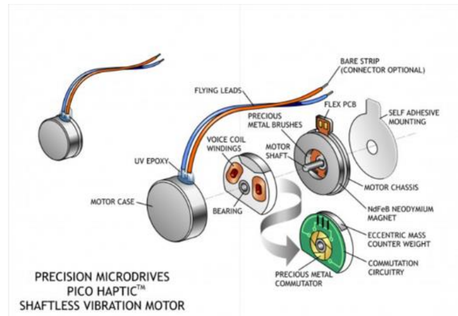

Fig. 3. Coin ERM motor

Fig. 3. illustrates the internal structure and components of a Pico Haptic Shaftless Vibration Motor, which is a type of ERM (Eccentric Rotating Mass) motor designed to produce vibration for haptic feedback. Here's a breakdown of the key parts shown in the image:

1. Motor Case: This is the outer shell that houses the components of the vibration motor. It is usually round and compact, resembling the shape of a coin.
2. Flying Leads: These are the electrical wires that connect the motor to the circuit, allowing the motor to receive power and signals to control the vibration.
3. Voice Coil Windings: A coil of wire inside the motor that, when electricity passes through it, creates a magnetic field. This field interacts with the motor's magnet to create rotation.
4. Bearing: The bearing allows the motor shaft to rotate smoothly with minimal friction, ensuring that the motor spins efficiently.
5. Motor Shaft: A small rod connected to the rotating part of the motor. The shaft spins when the motor is active.
6. Precious Metal Brushes: These are small electrical contacts that connect to the commutation circuitry, providing a continuous power connection as the motor rotates.
7. Flex PCB: A flexible printed circuit board that integrates the motor's electrical components, helping to keep the motor lightweight and compact.
8. Motor Chassis: The structural frame inside the motor that holds the components together.
9. Eccentric Mass Counterweight: A small, off-centered weight attached to the rotating shaft. This is what causes the vibration. As the motor spins, the uneven weight distribution creates centrifugal force, making the motor "wobble" and generate a vibration.
10. NdFeB Neodymium Magnet: A strong permanent magnet inside the motor that interacts with the voice coil to produce rotational movement.
11. Commutation Circuitry: The electronics inside the motor that manage the flow of electricity to the motor's

components, ensuring the motor spins in the correct direction.

Overall, this motor operates by spinning the eccentric mass counterweight, which produces a vibrating sensation due to the off-centered movement. This compact design makes it ideal for small devices that require tactile feedback, like handheld controllers, smartwatches, or phones.

B. DRV2605L: The haptic actuators have to be managed and controlled to deliver the desired result. Driver integrated circuits (ICs) perform this function [3]. Driver ICs are responsible for controlling primarily the power supply to the haptic actuator. DRV2605L from TI is a haptic actuator driver that reduces system complexity which has an integrated haptic effect library with 123 distinct haptic effects preloaded. This driver meets our design challenge as the driver should be compact that fits into our design, consumes less power, and produces precise haptic effect.

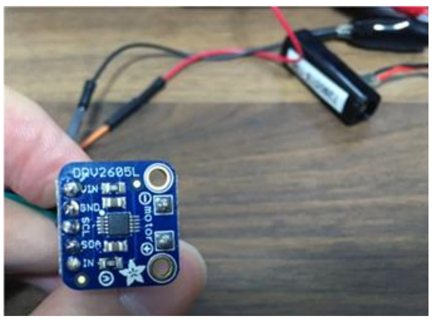

Fig. 4. DRV2605L

This chip shown in Fig. 4. is controlled over I2C communication. It produces a maximum frequency of up to 200Hz for the ERM motor to vibrate.

C. TCA9548A: The TCA9548A is a versatile I2C (Inter-Integrated Circuit) multiplexer designed to expand the I2C bus capability by allowing multiple devices with the same I2C address to coexist on a single bus [4]. This is achieved by isolating different I2C channels, enabling the master controller to communicate with each device individually.

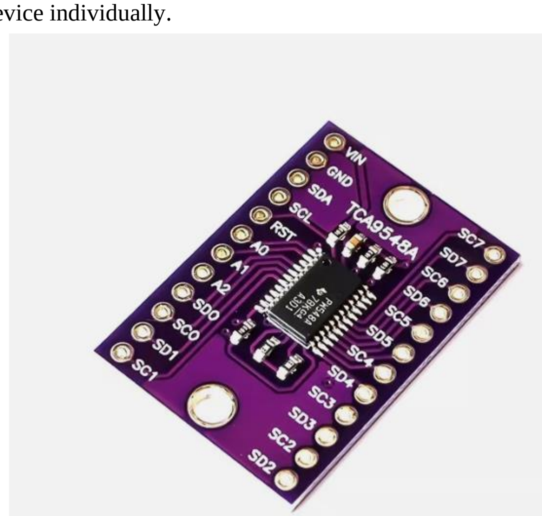

Fig. 5. TCA9548A

Key Features of this I2C mux shown in Fig. 5. is,

1. I2C Bus Multiplexing: It Provides 8 independent downstream I2C channels. Each channel can be individually enabled or disabled, ensuring no conflicts between devices.
2. Wide Operating Voltage: Supports a power supply range of 1.65V to 5.5V, making it compatible with a wide variety of systems.
3. Bidirectional Communication: Allows data to flow both from the master to the slave and vice versa.
4. Addressing Flexibility: Programmable I2C slave address using 3 hardware address pins, enabling up to 8 TCA9548A devices on the same bus.
5. Low Power Consumption: Operates with minimal power draw, suitable for battery-powered applications.
6. Isolation and Signal Integrity: Prevents crosstalk and interference by isolating each channel.

D. Design and Fabrication: Haptic gloves have 2 components: Power PCB and Flex PCB.

Power PCB as shown in Fig. 6. has ESP32 [5] microcontroller, 2 LiPo batteries, SPDT switch and flex pcb connectors. This power PCB is designed in Altium Software [6] and got it fabricated from JLCPCB. It is assembled in the lab and tested. The case for the Power PCB is designed in Autodesk Fusion software and 3D printed using Bamboo software.

Fig. 6. Power PCB

Our system consists of five flex PCBs as shown in Fig. 7., each dedicated to controlling one finger. Each flex PCB integrates a multiplexer and eight DRV2605L haptic drivers, with each driver connected to a motor. These PCBs interface with the Power PCB via connectors for efficient power distribution and control. The design of the flex PCBs was executed using Altium Designer, ensuring high precision and reliability. For manufacturing, we partnered with JLCPCB, leveraging their expertise to fabricate the PCBs with quality and accuracy. This setup forms the foundation of our haptic feedback system, providing robust control and functionality.

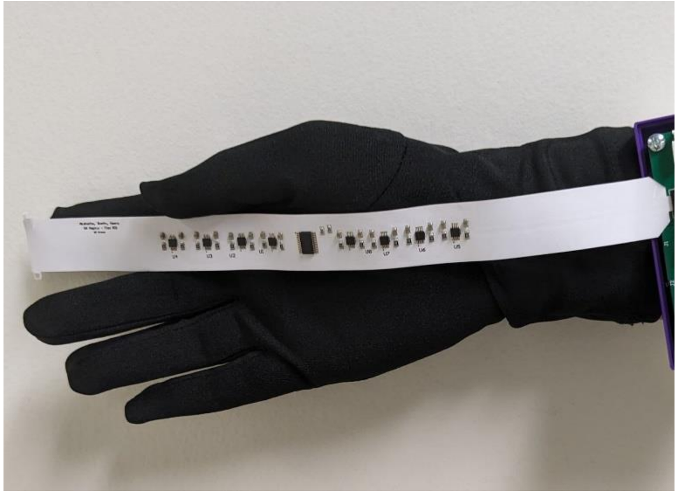

Fig. 7. Flex PCB

V. SOFTWARE SETUP

A. VR Application Details:

The VR application serves as the foundational component of the rehabilitation system, facilitating immersive and interactive motor skill enhancement tasks. Built using advanced frameworks, the application leverages state-of-the-art hand-tracking technologies and realistic physics to create a meaningful therapeutic experience.

B. Development Tools:

1) Unity Engine (Version: 2022.3.25f1): Powers the 3D VR environment, offering tools for rendering, physics, and interaction modeling.

2) C# with .NET Framework (Version: C# 13.0, .NET Standard 2.1): Scripting language for game mechanics, interaction logic, and hardware communication.

3) OpenXR Plugin: Facilitates compatibility across a range of VR headsets and devices, ensuring seamless performance.

4) XR Hands Package:

a) A specialized module within the XR framework that captures high-precision hand-tracking data *(refer to Fig. 8: Tracked virtual left-hand joints).*

b) Provides real-time mapping of hand joints, such as the wrist, fingers, and fingertips, to their virtual counterparts.

c) Enhances interaction fidelity by enabling complex gestures critical for rehabilitation tasks.

5) XR Interaction Toolkit:

a) Simplifies the development of natural hand and controller interactions in Unity.

b) Enables hand gestures like pinching, grabbing, and poking, which are essential for rehabilitation tasks.

C. Development Features:

1) Advanced Hand Tracking:

a) Hand joint data captured using the XR Hands Package and OpenXR Plugin is mapped in real-time to the VR environment *(refer to Fig. 8: Tracked virtual left-hand joints).*

b) High-resolution joint detection supports intuitive interactions, such as pinching, pointing, and grabbing.

c) Custom algorithms process raw joint data to ensure smooth and responsive interaction with virtual objects.

2) Physics Simulations:

a) Gravity, object mass, and surface friction are integrated to create lifelike interactions.

Example: Objects fall naturally upon release, with collisions accurately simulated based on their physical properties.

3) Audio and Sensory Features:

a) Task-Specific Audio Cues: Popping sounds for Task 1 *(refer to Fig. 9: Real-Time Hand Tracking and Object Popping in the VR Environment)* and object placement sounds for Task 2 *(refer to Fig. 10: Object Collection and Placement Using Realistic Grip Physics)* enhance immersion.

b) Background Music: Therapeutic and motivating tracks improve focus and engagement.

c) Haptic Feedback: Integrated with hand tracking to reinforce tactile sensations during interactions.

4) Gamified Rehabilitation Tasks:

Task 1: Object Popping

a) Designated objects must be popped while avoiding non-target items *(refer to Fig. 9: Real-Time Hand Tracking and Object Popping in the VR Environment)*.
b) Haptic feedback through the ESP32 adds a tactile dimension to enhance motor learning.

Focus: Reaction time, hand-eye coordination, and precise motor control.

Task 2: Object Collection

a) Users pick up scattered objects and place them into a container using realistic grip interactions *(refer to Fig. 10: Object Collection and Placement Using Realistic Grip Physics)*.
b) Dynamic physics simulations (e.g., mass, gravity, collision) enrich the realism.

Focus: Grip strength, fine motor skills, and sustained hand coordination.

D. Version Control & Iterative Development:

1) Software Revision Control:

a) GitHub was employed for version tracking, enabling efficient collaboration and rollback capabilities.

b) Commit messages documented updates such as improved hand-tracking algorithms and physics enhancements.

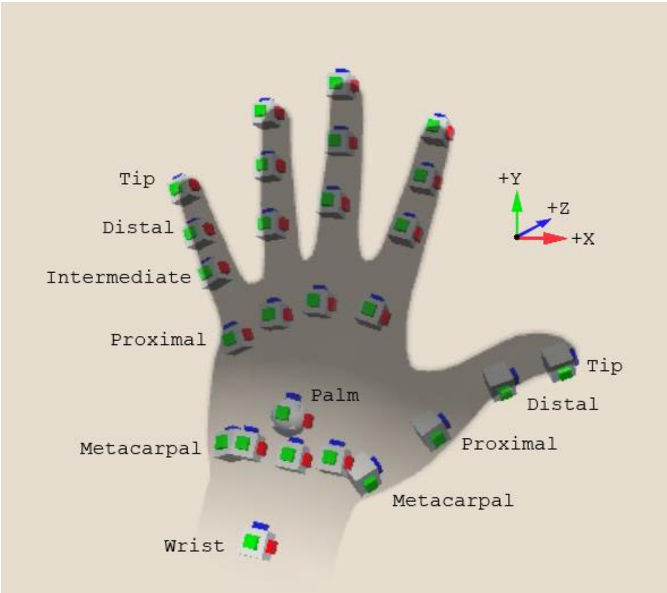

Fig. 8. Tracked virtual left-hand joints

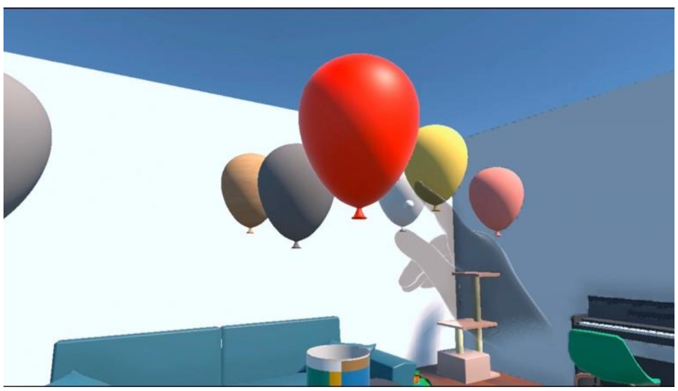

Fig. 9. Real-Time Hand Tracking and Object Popping in the VR Environment

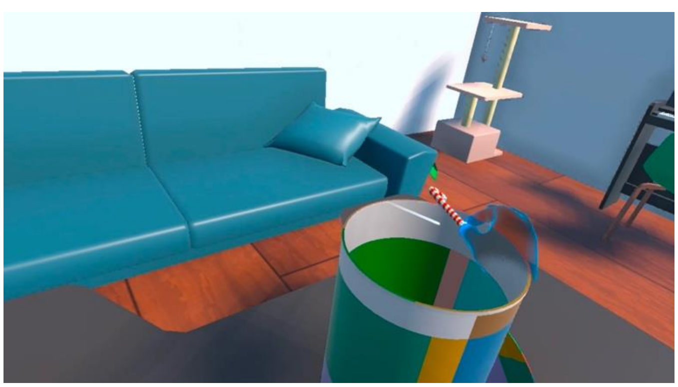

Fig. 10. Object Collection and Placement Using Realistic Grip Physics

VI. RESULTS

The Fig. 11. Shows the oscilloscope output of the ERM motor vibrating with 3 intensities - low, medium and high.

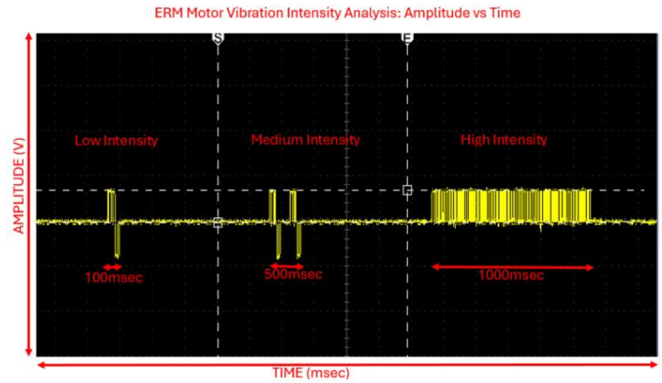

Fig. 11. Motor's Oscilloscope output

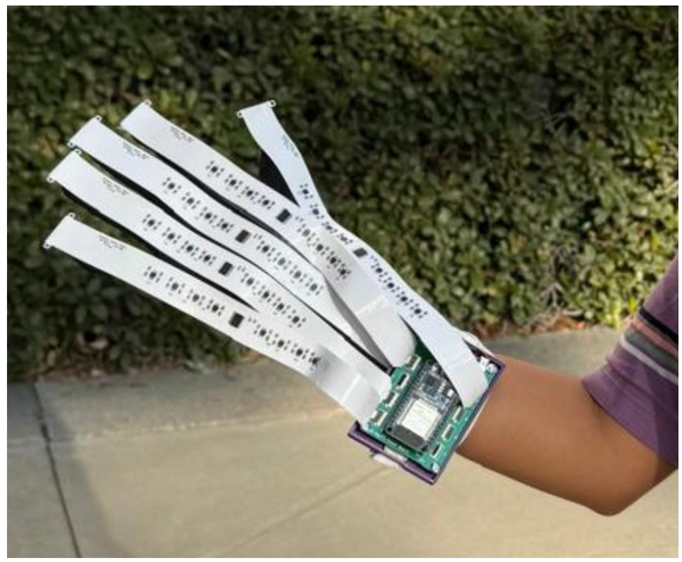

Fig. 12. Participant wearing the haptic hand glove designed.

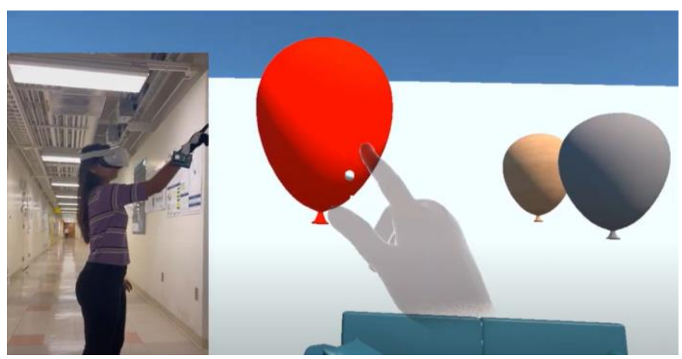

Fig. 13. Participant interacting with a virtual environment using the haptic feedback glove system.

VII. FUTURE SCOPE

1. Single Chip Integration for Multiple Actuators To further enhance the compactness and efficiency of the haptic feedback system, integrating control for multiple actuators onto a single microcontroller chip is a crucial development. This would reduce the hardware footprint, minimize interconnection complexity, and improve the overall reliability of the system. The integration would also

facilitate synchronized actuator operations, improving the fidelity of haptic feedback during rehabilitation exercises.

2. Battery Optimization for Long Run
Enhancing battery life is essential for continuous usage, especially in rehabilitation settings where sessions may extend over several hours. Future efforts will focus on optimizing power consumption through intelligent power management techniques, low-power mode utilization, and energy-efficient hardware. Additionally, exploring alternative power sources such as rechargeable or solar-assisted systems could contribute to sustainability and user convenience.
3. Bluetooth Integration for Internet-Free Communication
Integrating Bluetooth-based communication enables the system to operate seamlessly without dependency on the Internet. This ensures accessibility in remote areas or settings where Internet connectivity is unreliable. Low-latency and high-security Bluetooth protocols will be adopted to provide robust and uninterrupted data exchange between the VR system and the wearable device.
4. Cloud-Based Game Performance Analysis for Medical Feedback
Incorporating cloud services into the system allows for the storage and analysis of game performance data. The data can be processed to generate detailed progress reports and actionable insights for therapists and medical professionals. Real-time performance tracking, trend analysis, and personalized rehabilitation plans can be implemented to improve therapy outcomes.
5. Multi-User Connectivity for Collaborative Virtual Environment
Extending the platform to support multi-user connectivity will enable collaborative rehabilitation exercises. This feature could facilitate group therapy sessions, enhance social interaction, and allow therapists to monitor and interact with multiple users simultaneously. Advanced networking techniques and optimization for low-latency communication will ensure a smooth and immersive multi-user experience.

These advancements will expand the capabilities and utility of the haptic feedback system, making it a versatile tool for stroke rehabilitation and beyond.

VIII. CONCLUSION

This project demonstrates a novel approach to stroke rehabilitation by integrating haptic feedback within a virtual reality environment. By leveraging a custom-designed glove and actuators, the system provides real-time tactile sensations to patients, enhancing their motor skill recovery through interactive VR exercises. The solution not only bridges the gap between traditional therapy and modern technology but also ensures accessibility and motivation for in-home rehabilitation. This innovative combination of haptics, VR, and adaptive gameplay sets the foundation for a more effective and engaging rehabilitation framework, promising improved patient outcomes and paving the way for future advancements in rehabilitative care.

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