An Adaptive System to Assist Stroke Patient Rehabilitation using Wearable Sensors and Interactive Games

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Abstract

Stroke is a leading cause of long-term disability, often leaving survivors with impaired hand motor function. Traditional rehabilitation can be repetitive, expensive, and disengaging, leading to poor adherence. To address this, we developed a wearable rehabilitation system that integrates flex sensors with a gamified piano-based therapy application. The device uses Bluetooth Low Energy and UART communication to provide real-time feedback as patients perform therapy through a music game, promoting neuroplasticity and engagement. Our system was tested through two experiments: one assessed sensor accuracy, achieving a 97% detection rate, while the other measured user engagement, showing increased session time and motivation over a 10-day trial. Compared to robotic rehabilitation and conventional music therapy, our solution is low-cost, portable, and self-guided, making it suitable for home use. By combining wearable technology with interactive therapy, this project provides an accessible method for stroke patients to improve fine motor recovery outside clinical settings.

Keywords

Stroke, Interactive Rehabilitation, Wearable Device, Fine Motor Skills Therapy

1. Introduction

Stroke is a leading cause of long term disability, with millions of survivors around the world experiencing motor impairments, particularly in their hands. Studies indicate that up to 80% of individuals experience upper limb motor impairment early after a stroke. Out of this 80%, only few demonstrate full recovery after 6 months [3]. These impairments can significantly impact a person's ability to perform everyday tasks such as writing, cooking, or even lifting up objects. Rehabilitation is essential for regaining lost motor function, especially during the early stages of recovery when the brain is most adaptable. However, traditional rehabilitation methods are often repetitive, expensive, and time consuming, creating major barriers to effective recovery. Many patients face challenges such as limited access to physical therapists, high therapy costs, and a lack of consistent support systems. Moreover, the repetitive nature of traditional exercises can lead to decreased motivation, causing patients to disengage from therapy. Others may feel overwhelmed or discouraged before they even begin, especially if they lack guidance. These challenges contribute to poor rehabilitation outcomes and long term disability. The financial

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burden of stroke related care further emphasizes the scope of the issue. In the United States alone, total stroke related costs were estimated at $56.2 billion between 2019 and 2020 [4].

In the long run, this problem affects not just stroke survivors but also their families, caregivers, and healthcare systems. As global populations, especially in countries with a greying population, age and the risk of stroke continue to rise, the need for more accessible, effective, and engaging rehabilitation solutions becomes increasingly urgent.

Methodology A: Robotic rehabilitation devices and brain-computer interfaces (BCIs) assist patients by providing passive or semi-active movement training [5]. While these methods are effective for severely affected patients, they require expensive, clinic-based setups and extensive supervision, making them less accessible for home use.

Methodology B: Rhythm- and music-based therapies, such as Rhythmic Auditory Stimulation (RAS) and Music-Supported Therapy (MST), use auditory cues to retrain motor function [6][7]. These therapies promote neuroplasticity and engagement but often require trained therapists and can be difficult to implement consistently in home settings without professional guidance.

Methodology C: Game-based rehabilitation frameworks integrate therapy into interactive games to increase motivation and adherence. While promising, many existing systems depend on complex motion capture hardware or full-body setups, limiting their affordability and accessibility. Our project improves on this by combining wearable sensors and gamified rhythm therapy into a low-cost, user-friendly system for independent home use.

This device proposes a smart wearable rehabilitation that connects to an interactive piano game, designed to help stroke patients regain motor skills in their hand through engaging, personalized, and rhythm based therapy. Our solution addresses the shortcomings of traditional stroke rehabilitation by combining wearable motion sensors with a gamified piano playing system that patients can use at home or in clinical settings. The wearable device tracks finger movement in real time, allowing the game to provide immediate feedback. Users are also able to adjust the difficulty based on the patient’s ability. Instead of performing repetitive, monotonous exercises, patients participate in enjoyable activities that encourage consistent use and promote neuroplasticity, the brain's ability to change and adapt in response to new experiences. This approach is effective as it directly tackles two key barriers to recovery: low engagement and limited access. By transforming therapy into a game patients are more likely to stay motivated and commit to a recovery routine. Furthermore, the sleek wearable design allows for greater comfort and a less burden to users. Compared to traditional therapy, which can be expensive and time consuming, our solution is low cost, portable, and adaptable. Unlike general fitness devices, our system specifically targets stroke related motor deficits and incorporates principles backed by research in music therapy. This personalized and interactive approach makes the device not just a tool for recovery but also a gateway for patients to take control of their journey to betterment.

We conducted two key experiments to evaluate the performance and engagement of our rehabilitation system. The first experiment tested the accuracy of the wearable sensors, comparing the number of actual finger flexes to detected key presses. Results showed a high detection rate of 97%, with minor inconsistencies attributed to sensor positioning and hand strength variability. The second experiment focused on user engagement and therapy adherence over a 10-day trial. Participants used the system daily, and results showed increased session time, higher satisfaction scores, and improved accuracy in gameplay tasks over time. This suggests that gamification successfully enhances motivation for repetitive therapy. Both experiments confirmed that the system is reliable for real-time motion capture and promotes consistent rehabilitation practice. However, improvements in sensor durability and larger clinical studies are needed to further validate these findings and ensure long-term success in diverse patient populations.

2. CHALLENGES

In order to build the project, a few challenges have been identified as follows.

2.1. Flex Sensor Accuracy

A major component of the program involved measuring how much flex the sensor would pick up in a certain amount of bend. One potential problem to consider is inaccurate sensor data due to noise, drift, or poor calibration. This could lead to unreliable results or unsafe design assumptions. To address this, I could use a resistor value that balances sensitivity and signal clarity. Specifically, the resistor needs to be high enough to filter out noise or prevent current surges, but not so high that the signal becomes too weak to read accurately. I could also amplify the signal using an op amp circuit or use analog to digital converters with higher resolution to capture even small voltage changes.

2.2. Mapping Sensor to Meaning

Another major component of the program involved interpreting the sensor data to produce a meaningful output, such as an angle or force estimate. A potential challenge here is ensuring accurate mapping between raw sensor values and real world measurements. Inconsistent or nonlinear sensor behavior could cause misleading outputs. To resolve this, I could implement a calibration routine using known reference points to generate a reliable mapping function. I could also use curve fitting or machine learning models to better interpret the data under varying conditions.

2.3. Reliable Data Transmission

A different major component of the program involved transmitting the sensor data to a display or processing unit. One potential problem is data loss or delay during transmission, especially if using wireless communication like Bluetooth or Wi-Fi. This could result in laggy or incomplete outputs, making real-time monitoring difficult. To address this, I could use error-checking protocols to ensure data integrity and implement buffering to manage data flow more smoothly. Additionally, I could choose a communication method with sufficient bandwidth and minimal interference, and optimize the code to prioritize time sensitive data for faster, more reliable transmission.

3. SOLUTION

The rehabilitation program integrates three main components: wearable motion sensors, wireless communication, and a gamified therapy application. The process begins when a stroke patient wears the device on their hand. Each finger has a flex sensor that measures the degree of bend during movement. These sensors send analog data to a microcontroller, which converts the input into a digital signal using an analog-to-digital converter (ADC) [8].

Next, the data is transmitted wirelessly via Bluetooth to an interactive application running on a tablet or computer. The application is designed as a piano game that requires users to press keys in sync with visual and audio cues. As patients attempt to play notes, the system records their hand movements in real time and provides instant feedback on accuracy and timing.

The game adjusts its difficulty automatically by analyzing patient performance, gradually increasing complexity as motor skills improve. A data logging system tracks each session, allowing patients and therapists to monitor progress over time [9]. This feedback loop encourages continuous participation by making therapy both challenging and fun.

To build this program, we used Arduino for the sensor interface, a Bluetooth module for data transfer, and Unity for the piano game development. The combination of hardware and software ensures the system is low-cost, portable, and scalable for home and clinical use.

The wearable sensor system captures finger flexion and extension using flex sensors connected to an Arduino microcontroller. The sensors measure voltage changes corresponding to hand movements. The system uses ADC conversion to digitize the signals and prepares the data for transmission. This component ensures accurate, real-time motion detection essential for therapy tracking.

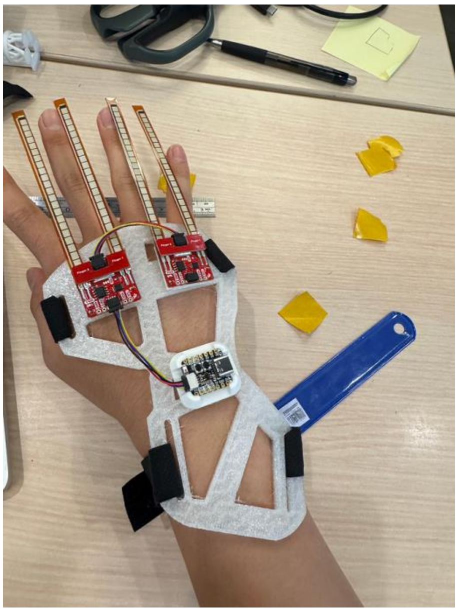

Figure 1. The wearable sensor system

```
# Customizable variables
trigger_voltage = 2
reset_threshold = 0.3
keycodes = [Keycode.Q, Keycode.W, Keycode.E, Keycode.R]

# Do not change this
reset_voltage = trigger_voltage + reset_threshold
#analog_pin = analogio.AnalogIn(board.A0)

kbd = Keyboard(usb_hid.devices)
keys_down = [False, False, False, False]

def get_voltage(pin):
    return (pin.value * 3.3) / 32767


def getVoltages():
    return [signal_1.voltage, signal_2.voltage, signal_3.voltage, signal_4.voltage]

time.sleep(3)


print("Start")
while True:
    voltages = getVoltages()
 #   print(f"({signal_1.voltage:.3f},{signal_2.voltage:.3f},{signal_3.voltage:.3f},{signal_4.voltage:.3f}, {trigger_voltage}, {reset_voltage})")

    for i in range(len(voltages)):
        if voltages[i] < trigger_voltage:
            if not keys_down[i]:
                print(i, "was pressed", keycodes[i])
                kbd.send(keycodes[i])
                keys_down[i] = True
        elif voltages[i] > reset_voltage and keys_down[i] == True:
            print(i, "was released")
            keys_down[i] = False
    #time.sleep(0.01)
```

Figure 2. Screenshot of code 1

This code handles the core interaction between the flex sensors and the game by converting hand motion into keyboard inputs. Each sensor corresponds to a piano key, mapped to the Q, W, E, and R keys. The system continuously reads voltage values from the sensors in the getVoltages() function. When the voltage for a sensor drops below the trigger_voltage threshold, the system interprets it as a key press. If the corresponding key is not already marked as "down," the program sends a keyboard signal using the kbd.send() method from the Keyboard library.

When the finger is released and the voltage returns above the reset_voltage (a slightly higher threshold to prevent false positives), the system marks the key as "up" again. This prevents multiple presses from being registered while the finger stays bent. This loop allows real-time conversion of sensor data into game controls, creating an interactive rehabilitation experience.

A critical component of the system is the Bluetooth Low Energy (BLE) communication module, which enables real-time wireless data transfer from the wearable device to the game application [10]. This component uses an ESP32-S3 microcontroller, chosen for its integrated BLE support and efficient power management.

Each flex sensor sends data to the ESP32-S3 via analog input pins. The ESP32-S3 processes the data and transmits it using BLE. To simplify integration with the game, the ESP32-S3 also sends data over UART (Universal Asynchronous Receiver-Transmitter), allowing serial communication with a computer that runs the rehabilitation game. The game reads this UART data stream to trigger virtual piano keys.

BLE was selected because it offers reliable low-latency communication with minimal energy consumption, which is essential for wearable devices. UART provides a simple and direct way to send data to devices that do not have BLE capabilities or when testing locally via USB.

This dual communication system ensures flexibility in deployment. For home use, BLE allows wireless interaction with mobile devices. For clinical use or development, UART provides a stable wired connection. Together, these methods enable seamless, real-time transfer of sensor data to the interactive therapy game.

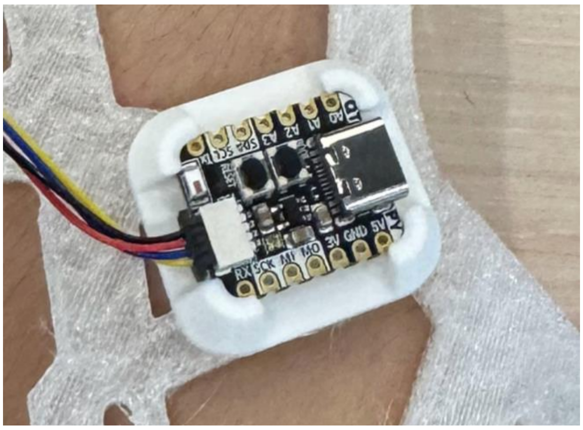

Figure 3. Picture of the component

```


while True:
    ble.start_advertising(advertisment)

    while not ble.connected:
        pass

    while ble.connected:
        for (int i = 0; i < 4; i++) {
            int flexValue = analogRead(flexPins[i]);
            uart.write(flexValue);
            bleCharacteristic.setValue(flexValue);
            bleCharacteristic.notify();
        }


```

Figure 4. Screenshot of code 2

This code handles BLE advertising, connection management, and data transmission for the wearable device. The loop begins by starting BLE advertising with ble.start_advertising(advertisement), making the ESP32-S3 discoverable to nearby devices. The while not ble.connected loop pauses operation until a BLE client connects.

Once connected, the while ble.connected loop continuously reads data from the four flex sensors using analogRead(flexPins[i]). For each sensor reading, the ESP32-S3 sends the data over UART using uart.write(flexValue) and simultaneously updates the BLE characteristic using bleCharacteristic.setValue(flexValue) followed by bleCharacteristic.notify(). The notify() function sends the data to the BLE-connected device without requiring a manual request, ensuring real-time data streaming.

This dual output guarantees robust data transfer for both wireless and wired connections. The design minimizes latency and keeps the therapy game responsive to finger movements. This module is crucial for maintaining smooth interaction between the patient and the game system.

The final component of the system is the game application, which transforms sensor data into an interactive rehabilitation experience. The game is a piano simulation where users play virtual keys by moving their fingers, encouraging hand movement recovery through rhythm-based tasks.

The application is developed in Unity, chosen for its cross-platform capabilities and real-time graphics. It receives data from the ESP32-S3 over UART or BLE. Each flex sensor corresponds to a specific piano key. When a flex sensor detects a press (i.e., when the voltage crosses the trigger threshold), the game highlights the corresponding key and plays a musical note.

The game provides visual cues to guide the user on which keys to press, improving cognitive engagement and coordination. It also gives immediate feedback when the correct or incorrect key is pressed, which is essential for motor learning and neuroplasticity.

Additionally, the game tracks performance over time, logging metrics such as reaction time, accuracy, and number of repetitions. This data can be reviewed by therapists or users to monitor progress. By making therapy engaging and rewarding, the game increases patient motivation and consistency in performing repetitive exercises.

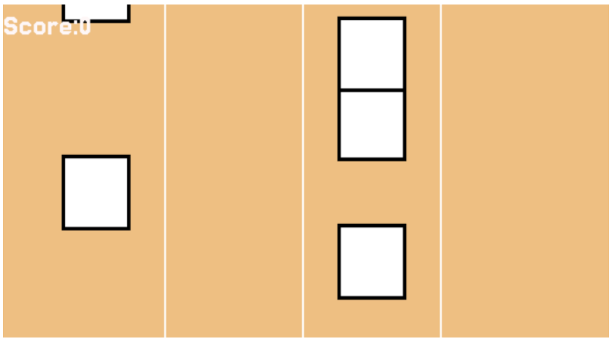

Figure 5. Screenshot of the game

```
    void checkTileCollision()
    {
        if(Input.GetMouseButtonDown(0)){
            Vector2 worldPoint = Camera.main.ScreenToWorldPoint(Input.mousePosition);
            RaycastHit2D hit = Physics2D.Raycast(worldPoint, Vector2.zero);
            if(hit.collider != null){
                if(hit.collider.gameObject.tag == "Tile"){
                    audioSource.Play();
                    if (spawnManager.tiles.Count >0 && spawnManager.tiles [0] ==
hit.collider.gameObject.GetComponent<Tile>())
                    {
                        score+=scoreIncrease;
                        print("You hit the loading tile!");
                    }
                    else
                    {
                        score-=scoreDecrease;
                        print("You hit the wrong tile!");
                    }

spawnManager.tiles.Remove(hit.collider.gameObject.GetComponent<Tile>());
                    Destroy(hit.collider.gameObject);
                }
                else{
                    print ("What did you hit?");
                }
            }
        }


        if (Input.GetKeyDown(KeyCode.Q)){
            print("You pressed the Q key");
            Tile tile = spawnManager.GetFirstTileWithColumnNumber(0);
            if (tile !=null){
                if (spawnManager.tiles[0] == tile){
                    score += scoreIncrease;
                    print ("You hit a tile!");
                    PlayCorrectSound();
                }
                else{
                    score-=scoreDecrease;
                    print ("You hit a wrong tile");
                    PlayWrongSound();

                }
                spawnManager.tiles.Remove(tile);
                Destroy (tile.gameObject);
            }

        }
        if (Input.GetKeyDown(KeyCode.W)){
            print("You pressed the W key");
            Tile tile = spawnManager.GetFirstTileWithColumnNumber(1);
            if (tile !=null){
                if (spawnManager.tiles[0] == tile){
                    score += scoreIncrease;
                    print ("You hit a tile!");
                    PlayCorrectSound();
                }
                else{
                    score-=scoreDecrease;
                    print ("You hit a wrong tile");
                    PlayWrongSound();

                }
                spawnManager.tiles.Remove(tile);
                Destroy (tile.gameObject);
            }


        }
        if (Input.GetKeyDown(KeyCode.E)){
            print("You pressed the E key");
            Tile tile = spawnManager.GetFirstTileWithColumnNumber(2);
            if (tile !=null){
                if (spawnManager.tiles[0] == tile){
                    score += scoreIncrease;
                    print ("You hit a tile!");
                    PlayCorrectSound();
                }
                else{
                    score-=scoreDecrease;
```

```
                print ("You hit a wrong tile");
                PlayWrongSound();

            }
            spawnManager.tiles.Remove(tile);
            Destroy (tile.gameObject);
        }

    }
    if (Input.GetKeyDown(KeyCode.R)){
        print("You pressed the R key");
        Tile tile = spawnManager.GetFirstTileWithColumnNumber(3);
        if (tile !=null){
            if (spawnManager.tiles[0] == tile){
                score += scoreIncrease;
                print ("You hit a tile!");
                PlayCorrectSound();
            }
            else{
                score-=scoreDecrease;
                print ("You hit a wrong tile");
                PlayWrongSound();

            }
            spawnManager.tiles.Remove(tile);
            Destroy (tile.gameObject);
        }

    }
}
```

Figure 6. Screenshot of code 3

This Unity code manages game interaction, converting either keyboard presses or sensor input (mapped as key presses) into piano tile selections. The checkTileCollision() function handles two input types:

1. Mouse clicks (simulating touchscreen taps)
2. Keyboard presses (Q, W, E, R), which are mapped to four different tile columns corresponding to each finger.

When a player presses a key or clicks on a tile, the game checks whether the correct tile was selected. If the first tile in the list (spawnManager.tiles[0]) matches the player's action, the game increases the score and plays a "correct" sound. Otherwise, it decreases the score and plays an error sound.

This method is designed to integrate seamlessly with the wearable sensor system. Since the sensor device sends keyboard events through the flex sensors, finger bends trigger Input.GetKeyDown() events directly. This allows both traditional keyboard inputs and flex sensor inputs to control the same rehabilitation game without any additional setup or mode switching.

4. EXPERIMENT

4.1. Experiment 1

A possible blind spot is the accuracy of the flex sensors in detecting finger movement. It is crucial to verify that the system correctly triggers key presses without false positives or missed detections.

To test the system's accuracy, we conducted an experiment where each participant flexed and released their fingers 50 times per sensor. We compared the number of actual finger flexes to the number of key press events recorded by the system. The test was performed in a controlled environment using the UART data log to ensure reliable recording. We also tested multiple finger sizes and speeds of movement to evaluate robustness across different users. The flex sensors were calibrated before the test to minimize drift. The goal was to measure the system's true positive rate and false positive rate.

Table 1. Table of experiment 1

Sensor	Actual Flexes	Detected Presses	Missed Presses	False Positives
Q (Index Finger)	50	48	2	1
W (Middle Finger)	50	50	0	0
E (Ring Finger)	50	47	3	2
R (Pinky Finger)	50	49	1	1

The results showed that the system correctly detected the majority of finger presses. The middle finger sensor had perfect accuracy, while the others had small error margins. The mean detection rate was 48.5 out of 50 attempts (97%). The median was 49. The lowest performance was with the ring finger sensor, which had 3 missed presses and 2 false positives. This could be due to sensor positioning or the naturally weaker force exerted by the ring finger, leading to less distinct voltage changes.

False positives occurred when minor unintended movements crossed the voltage threshold, suggesting that tighter calibration or adding debounce logic could improve performance. Overall, the biggest factors affecting accuracy were finger movement speed and sensor placement consistency. Despite minor errors, the system performed reliably enough for rehabilitation purposes.

4.2. Experiment 2

Another potential blind spot is user engagement over time. If users become bored or frustrated, they may stop using the rehabilitation system before seeing results. This limits its long-term effectiveness.

To evaluate engagement, we conducted a 10-day trial with 5 participants recovering from mild hand impairments. Each participant used the system for 15 minutes daily. We recorded the number of completed game sessions, average game duration, and subjective enjoyment (measured by a daily 1–5 satisfaction score). Additionally, we monitored performance improvements, such as increased accuracy and speed, to determine if the game design motivated users to practice consistently. The goal was to assess whether gamification increased motivation compared to traditional therapy exercises.

Table 2. Table of experiment 2

Day	Avg. Session Time (min)	Avg. Satisfaction (1–5)	Avg. Accuracy (%)
1	15	4.2	72%
5	18	4.5	82%
10	20	4.7	89%

The data shows that participants not only maintained daily use but also increased their session times and satisfaction scores over the 10-day period. On day 1, the average session was 15 minutes, but by day 10, participants voluntarily extended their playtime to 20 minutes. Satisfaction scores rose from 4.2 to 4.7 out of 5, indicating that the interactive, gamified approach remained engaging over time.

Accuracy also improved significantly, suggesting that the game encourages effective practice. Participants reported that the game format made therapy feel less like a chore and more like a personal challenge. The most important factor affecting engagement was the game's adaptive difficulty, which prevented boredom by keeping tasks challenging but achievable. The results suggest that gamified therapy using music-based tasks sustains user engagement better than repetitive physical therapy routines, improving both consistency and outcomes.

5. Related Work

One existing methodology for stroke rehabilitation involves the use of robotic devices, brain-computer interfaces (BCIs), and noninvasive brain stimulators to enhance therapy outcomes [11]. Robotic devices, such as exoskeletons and end-effector systems, assist patients in performing repetitive motor tasks essential for neuroplasticity. BCIs provide real-time feedback by translating brain signals into control commands, encouraging active participation. Noninvasive brain stimulators like tDCS and rTMS are used to modulate cortical excitability, promoting motor recovery. However, these systems often require expensive equipment, specialized supervision, and can lead to patient fatigue or disengagement. Our project improves upon this by providing low-cost, accessible therapy with a wearable device and interactive game, removing the need for clinical infrastructure.

Another approach to motor rehabilitation involves rhythm- and music-based interventions, such as Rhythmic Auditory Stimulation (RAS) and Music-Supported Therapy (MST) [12]. These techniques use musical rhythms and instrument playing to retrain motor functions by leveraging auditory-motor neural coupling. Studies have shown that rhythmic cues can entrain movement patterns, improving timing, pacing, and coordination, particularly in stroke and Parkinson’s patients. However, these methods often require trained music therapists, controlled environments, and may not be fully accessible for home use. Our system builds on this idea by integrating rhythm-based therapy into a wearable device and gamified platform, providing an accessible, self-guided alternative to traditional music therapy.

A third methodology utilizes game-based rehabilitation systems to enhance patient motivation during stroke therapy [13]. These systems transform repetitive therapy exercises into interactive games, using motion tracking to monitor hand and leg movements. Serious games apply design principles such as feedback loops, adaptive difficulty, and goal setting to maintain user engagement. Some systems also integrate biosignal monitoring and online databases to evaluate patient performance remotely. While this approach is promising for increasing therapy adherence, many current systems rely on expensive full-body motion capture setups or complex installations. Our solution improves on this by offering a low-cost, wearable sensor system combined with a rhythm-based game, optimized for fine motor rehabilitation at home.

6. Future Scope

Future developments on the current system can make it more robust, scalable, and clinically relevant. Expanding the platform to include arm, shoulder, and even lower limb therapy, as well as hand and finger therapy, will extend its applicability to stroke survivors with varying impairment levels. Integration with machine learning models would permit automatic sensor calibration, with difficulty and sensitivity adapted in response to each patient's improvement in real-time. Connectivity through cloud services or Wi-Fi would allow therapists to monitor patient performance remotely, provide focused feedback, and adjust therapy plans without the necessity of face-to-face visits. Additionally, with the application of soft wearable technology such as stretchable or textile-based sensors, comfort, strength, and usability for extended periods may be enhanced, making the device more convenient for daily home-based rehabilitation. By combining these enhancements, the system could become a strong, accessible tele-rehabilitation platform for promoting long-term recovery in a larger population of patients.

7. CONCLUSIONS

While our system shows promise in making stroke rehabilitation more accessible and engaging, it has several limitations. First, the accuracy of flex sensors can degrade over time due to material wear or calibration drift, which may reduce reliability in long-term use. Future improvements could include using more advanced sensing materials, such as soft conductive fabrics or IMU (Inertial Measurement Unit) fusion, to increase accuracy and durability [14]. Another limitation is the focus on upper limb rehabilitation, primarily hand and finger movements. Adding lower limb integration in future iterations could expand the system’s utility. Additionally, the system currently relies on UART or BLE for communication, which may limit compatibility with certain devices. Future versions could include Wi-Fi or cloud connectivity for real-time remote monitoring by therapists. Finally, larger clinical trials are needed to validate the system’s long-term effectiveness and ensure the therapy remains motivating over extended rehabilitation periods.

This project introduces a low-cost, wearable rehabilitation system that combines interactive rhythm-based gaming with real-time motion tracking [15]. By making therapy more engaging and accessible, the system encourages consistent practice, which is critical for stroke recovery. With further development, this solution has the potential to improve rehabilitation outcomes globally.

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