

Upper Limb Physical Rehabilitation System Through Video Games Controlled by EMG Signals

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Abstract— *Conventional physical therapies for patients with motor limitations are often repetitive and lack motivational elements, which hinders adherence and reduces treatment effectiveness. This study focused on the development of an interactive system based on electromyographic (EMG) signals to control video games designed in Unity, with the aim of enhancing patient motivation and facilitating motor rehabilitation through gamification. The system generates real-time control commands that enable interaction with video games specifically designed to promote the repetition of functional movements. Experimental validation showed improvements in patient performance across the games, while user satisfaction questionnaires reported positive experiences in ease of use, functional stimulation, and motivation. The system was also validated by a clinical professional, confirming its therapeutic potential. These results indicate that EMG-controlled video games not only enhance motivation but also strengthen treatment effectiveness, offering an innovative alternative to traditional therapies.*

Keywords— *assistive technology, EMG signals, physical rehabilitation, thresholding, video games*

I. INTRODUCTION

Musculoskeletal disorders are among the leading causes of global disability, affecting approximately 1.71 billion people, with a significant impact on quality of life due to the functional limitations they impose. Neurological conditions such as stroke and unilateral spastic cerebral palsy in children often severely compromise upper limb mobility, restricting independence in daily activities [1], [2], [3].

Although conventional physical rehabilitation is effective in restoring motor function, it faces critical challenges such as repetitive routines, low patient adherence, and limited personalization, which reduce long-term consistency and effectiveness [4], [5]. To address these limitations, emerging technologies such as therapeutic video games controlled by surface electromyographic signals (sEMG) have shown promise in enhancing rehabilitation by transforming voluntary muscle contractions into interactive commands for virtual tasks [6], [7], [8].

Surface electromyography is a non-invasive technique that records the electrical activity generated by muscle contractions, widely applied in both diagnostic procedures and human-machine interface control [5], [9].

Recent studies have reported the development of rehabilitation platforms integrating EMG into serious games, demonstrating improvements in neuromuscular coordination, muscle activation, and user motivation [7], [10], [11], [12], [13]. For instance, Ghassemi et al. (2019) designed an EMG-

controlled serious game for post-stroke patients, observing increased muscle activation and functional improvements in the upper limbs [10]. Seo et al. (2022) employed a similar system to retrain hand muscle activation patterns after stroke, while Boulay et al. (2024) implemented EMG-feedback games in children with spastic cerebral palsy, achieving significant gait improvements [1], [11]. Toepp et al. (2023) further proposed a biofeedback system for personalized interventions in distributed muscles, emphasizing the importance of advanced EMG signal analysis for targeted therapies [12].

Despite these research advances, the widespread adoption of EMG-based rehabilitation technologies in clinical practice remains significantly constrained by multiple barriers, including high equipment costs, limited accessibility, and insufficient technical infrastructure in resource-limited settings [14], [15]. Campanini et al. (2020) identified that technical barriers persist due to relatively high equipment prices, insufficient market demand, and a pervasive lack of user-friendly devices, which collectively hinder the translation of research findings into routine clinical applications [14]. Commercial clinical-grade EMG systems typically range from €15,000 to €20,000, rendering them economically inaccessible for many rehabilitation centers, particularly in developing countries [16].

Recent efforts have focused on developing low-cost alternatives using open-source platforms such as Arduino-based systems, which have demonstrated acceptable reliability for educational and research purposes when properly calibrated [17]. Garouche and Thamsuwan (2023) developed a low-cost portable EMG system specifically for field measurements, demonstrating that cost-effective solutions can achieve adequate signal quality for rehabilitation applications [18]. Similarly, Pradon et al. (2024) evaluated low-cost EMG systems in hemiparetic patients, finding good to very good correlation with reference systems during functional tasks, suggesting the viability of accessible EMG technology for clinical gait analysis [19].

However, significant challenges remain regarding standardization, clinical validation, and the development of comprehensive training programs to ensure competent operation and interpretation of these cost-effective systems [14], [20]. The economics of rehabilitation technology have created a critical gap between advanced research capabilities and clinical implementation, underscoring the urgent need for affordable, validated solutions that maintain therapeutic efficacy while improving accessibility in diverse healthcare contexts [15], [16].

The therapeutic potential of these platforms expands with the use of game engines such as Unity, which enables immersive environments with gameplay dynamics tailored to clinical objectives, improving user experience and adherence to treatment [21], [22]. Literature highlights that combining Unity with signal processing algorithms in MATLAB facilitates EMG data interpretation, filtering, and extraction of quantitative metrics such as VRMS and FFT, which are essential for evaluating activation intensity during therapy [23], [24].

This study builds upon previous work by Enamorado and Zuniga (2025), titled "Therapy with audiovisual feedback using EMG signals in arms affected by fracture in men aged 20-29", who developed two video games in Python and Microsoft Visual Studio to translate biceps brachii contractions into control commands [25], shifting the therapeutic focus from the biceps brachii to the forearm and wrist joint.

The proposed system acquires EMG signals through a surface sensor placed on forearm musculature (particularly the flexor and extensor carpi groups), connected to an Arduino UNO R3 microcontroller. After applying band-pass filtering with Butterworth algorithms in MATLAB, the processed data is integrated into Unity. Three video games were specifically designed—**Dino Game, Alien Attack, and Endless Runner**—to promote essential wrist movements (extension, flexion, and coordinated control), addressing key functional deficits in conditions such as post-stroke hemiparesis or repetitive strain injuries [26], [27]. This gamified approach aims to improve wrist range of motion, strength, and motor control through repetitive, engaging tasks.

II. METHODOLOGY

The system development was structured into three main phases: video game design, acquisition and processing of electromyographic (EMG) signals, and system integration. The study followed a quantitative and experimental methodology, in which numerical data on muscle activity were collected during the execution of a motor rehabilitation protocol assisted by video games, through EMG signal recording.

The system allowed for the configuration of personalized parameters for each user, in order to adapt the interaction and rehabilitation conditions to their individual characteristics. This research specifically focuses on wrist joint rehabilitation through forearm muscle activation, extending previous work centered on upper limb rehabilitation.

A. Participant Selection

A total of 20 healthy individuals were recruited through convenience sampling to participate in the study. Participant selection was guided by predefined eligibility criteria intended to ensure a homogeneous neuromuscular profile across volunteers. The methodological framework established an inclusion range of 17–25 years, as this age group typically exhibits stable neuromuscular performance, reduced variability in muscle activation patterns, and consistent skin impedance for EMG acquisition. The study was not conducted with

individuals presenting pathologies due to limited access to clinical populations and, more importantly, to avoid interfering with ongoing therapeutic processes of patients. In this initial stage, the primary objective was to validate the functionality of the system and ensure the proper design and development of the therapeutic video games before applying them in clinical rehabilitation contexts.

Additional inclusion considerations included the absence of diagnosed neuromuscular disorders and no upper-limb injuries within the previous six months, since such conditions could alter muscle recruitment strategies or compromise the reliability of the recorded signals. Although these criteria primarily served as methodological guidelines, recruitment focused on healthy volunteers whose characteristics aligned with the intended demographic. Individuals presenting dermatological conditions at electrode placement sites were excluded to prevent interference with electrode adhesion and signal quality.

B. System Components and Architecture

The system integrates three main components operating in real time: surface EMG acquisition hardware, signal processing algorithms, and therapeutic video games developed in Unity. A generic surface EMG sensor was used to record muscle activity from the forearm, specifically targeting the flexor and extensor carpi muscle groups responsible for wrist flexion and extension. The electrode configuration included two active electrodes placed over the muscle bellies and a ground electrode positioned on the elbow to stabilize the signal. This setup, illustrated in Fig.1, was connected to an Arduino UNO R3 microcontroller, which handled signal acquisition and transmission for subsequent processing and interaction with the game environment.

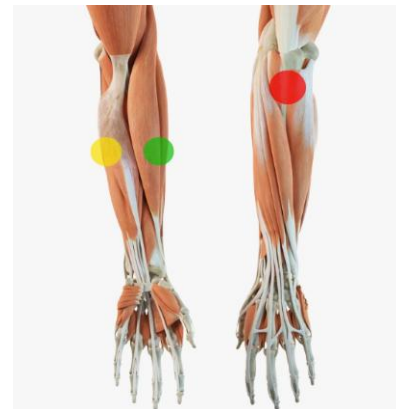


Fig. 1 Electrode placement on forearm muscles for wrist movement detection.

C. Signal Processing and Calibration Protocol

A calibration protocol was implemented for each participant before therapy sessions. The process consisted of four main steps: First, a resting baseline was established where participants maintained a relaxed forearm. Second, active calibration was performed through wrist flexion and extension

movements. Third, raw sensor readings (0-1023 range) were linearly mapped to an optimized range of 0-140. Fourth, individual activation thresholds were calculated based on calibration data, with threshold crossings generating specific action commands in each game. The main signal-processing parameters used during this procedure are summarized in Table I.

TABLE I
SIGNAL PROCESSING AND ACTION MAPPING PARAMETERS

Parameter	Description
Raw ADC range	0–1023 (10-bit Arduino ADC)
Mapped range	0–140 (optimized for processing)
Calibration duration	2–3 minutes per participant
Communication protocol	Serial communication at 9600 baud
Command format	Plain text strings (JUMP, SHOOT, LEFT, RIGHT)

The mapping between specific wrist movements and corresponding game actions is detailed in Table II. This mapping was consistent across all participants, with only the activation threshold being personalized during calibration.

TABLE II
THERAPEUTIC OBJECTIVES AND DESIGN CHARACTERISTICS

Video Game Parameter	Target Movement Description	Primary Objective	Game Design Features
Dino Game Raw ADC range	Wrist Extension 0–1023 (10-bit Arduino ADC)	Improve timing and coordination	Side scrolling platformer with obstacle avoidance
Allien Attack Mapped range	Wrist Flexion 0–140 (optimized for processing)	Develop isometric strength	Space shooter with progressive difficulty Space shooter
Endless Runner Calibration duration	Alternating movements 2–3 minutes per participant	Enhance coordination and precision	Infinite runner with increasing speed

D. Therapeutic Video Games Design

Three video games were specifically designed and developed in Unity to target different aspects of wrist rehabilitation. Each game incorporated gameplay mechanics aligned with functional therapeutic exercises, allowing users to interact with the system through specific wrist and hand movements captured via surface EMG.

1) *Dino Game: Wrist Extension Training*: The DinoGame was designed to promote wrist extension through a simple and intuitive movement: lifting the hand upward. In this side-scrolling platformer, the character advances automatically through a desert environment, and the user must raise the wrist to trigger the jump action. When the EMG signal surpasses the calibrated threshold associated with wrist extension, the system

sends the “JUMP” command to Unity, causing the character to leap over obstacles such as cacti and rocks. Fig. 2 provides a visual reference of the game.



Fig. 2 Dino Game interface showing character and obstacles for wrist extension training

This game aims to improve timing, coordination, and activation control of wrist extension, a movement essential for functional tasks involving hand opening and object release. Immediate visual feedback reinforces correct execution and helps refine motor accuracy.

2) *Alien Attack: Grip Strength and Flexion Training*: The game focuses on developing grip strength and controlled wrist flexion through a functional isometric exercise: squeezing and releasing a soft ball. In this space-themed shooter, the player controls a spacecraft that fires projectiles when the user performs a voluntary contraction by pressing the ball. Fig. 3 illustrates the visual layout of the game. The EMG signal generated during the squeeze activates the “SHOOT” command, allowing the player to eliminate incoming alien targets.



Fig. 3 Alien Attack game environment for grip and wrist flexion training

This design supports the development of sustained isometric strength, endurance, and fine control of flexor muscle activation. Difficulty can be adjusted by modifying the frequency and speed of enemy waves, enabling progressive therapeutic challenges.

3) *Endless Runner: Lateral Wrist Movement Training*: Endless Runner was developed to train rapid directional control through lateral wrist movements. Instead of flexion–extension, this game requires the user to move the hand toward the left or

right side to navigate the character through an endless obstacle course. Each directional movement is mapped to a specific EMG activation pattern, triggering the “LEFT” or “RIGHT” command in Unity.



Fig. 4 Endless Runner game for lateral wrist movement training

The game promotes controlled lateral deviations of the wrist, improving reaction time, precision, and coordination. As the speed and density of obstacles increase, users must execute faster and more accurate directional movements, supporting the development of functional motor control.

E. System Integration and Communication

Arduino communicated with Unity via serial port, sending plain text commands that were interpreted by C# scripts within each game to trigger corresponding therapeutic actions. Each game contained specialized scripts that monitored the serial port for incoming commands and translated them into immediate in-game responses. This integration ensured that muscle activations were directly linked to visual feedback within the gaming environment, creating a closed-loop system for motor learning and rehabilitation.

F. Experimental Procedure

The experimental sessions followed a structured procedure designed to standardize the rehabilitation protocol across all participants represented in Fig.5. Each session began with participant arrival and briefing, where the procedure was explained and informed consent obtained. This was followed by an initial assessment screening for wrist injury history.

The calibration phase involved EMG sensor calibration and individual threshold determination. Participants performed wrist flexion and extension movements while the system recorded signal characteristics to establish personalized activation thresholds. A critical aspect of the system design is that EMG signals are not continuously monitored or recorded during gameplay. Instead, the system only detects when the muscle activation threshold is crossed, triggering corresponding in-game actions with visual feedback.

For therapy selection, all 20 participants completed the full three-game sequence: Dino Game, Alien Attack, and Endless Runner. During therapy sessions, participants played assigned games using EMG-controlled commands. When muscle activation exceeded the calibrated threshold, the system sent the corresponding action command to Unity, with successful

threshold crossing immediately confirmed by in-game visual feedback.

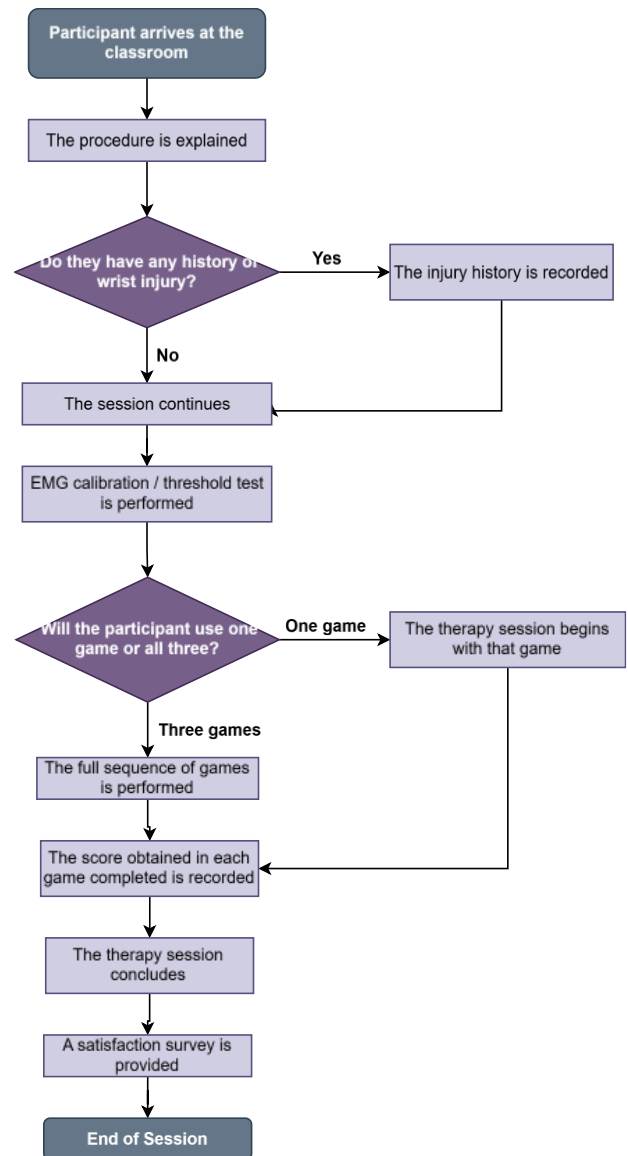


Fig. 5 Flowchart of the experimental procedure for EMG-controlled rehabilitation sessions

Each session concluded with a final evaluation through a satisfaction questionnaire covering overall user experience, physical comfort, perceived performance and control, therapeutic usefulness of the games, and motivation and engagement levels.

The experimental session followed a structured and sequential protocol, with an estimated total duration ranging between 15 and 20 minutes per participant. Upon arrival, participants received a brief explanation of the procedure, which lasted approximately 3 to 5 minutes, followed by an initial assessment lasting 1 to 2 minutes to verify eligibility and confirm the absence of recent wrist injuries. Subsequently, a

calibration phase of 2 to 3 minutes was conducted to adjust the EMG system parameters and establish individualized activation thresholds.

After calibration, a short therapy selection stage of approximately 1 minute was performed, after which participants engaged in the therapeutic gameplay phase. This phase consisted of three EMG-controlled video games and represented the longest portion of the session, with an estimated duration of 12 to 15 minutes. Upon completion of the gameplay, the session concluded with a brief wrap-up stage lasting 1 to 2 minutes.

Finally, participants completed a post-session evaluation, including a satisfaction questionnaire, which required an additional 3 to 5 minutes, followed by session closure activities lasting 1 to 2 minutes. For each of the 20 participants, multiple data types were systematically collected. Performance metrics included the final scores in each video game. Calibration data comprised individual activation thresholds, signal characteristics during calibration, and mapping parameters for each participant.

User experience was assessed through a satisfaction questionnaire using a 5-point Likert scale, measuring perceived effectiveness for wrist rehabilitation, motivation, and engagement levels. Additional open-ended feedback was collected to capture qualitative insights into the system's usability and therapeutic value.

All testing was conducted in controlled university classroom environments to ensure consistent conditions. The testing space was private and quiet, minimizing external distractions that could affect participant concentration or EMG signal quality. The environment was prepared to minimize electromagnetic interference from other electronic devices, ensuring accurate EMG signal recording. Standardized equipment setup was maintained across all sessions to ensure comparability of results. Refer to Fig. 6 for a visual representation of the testing setup.

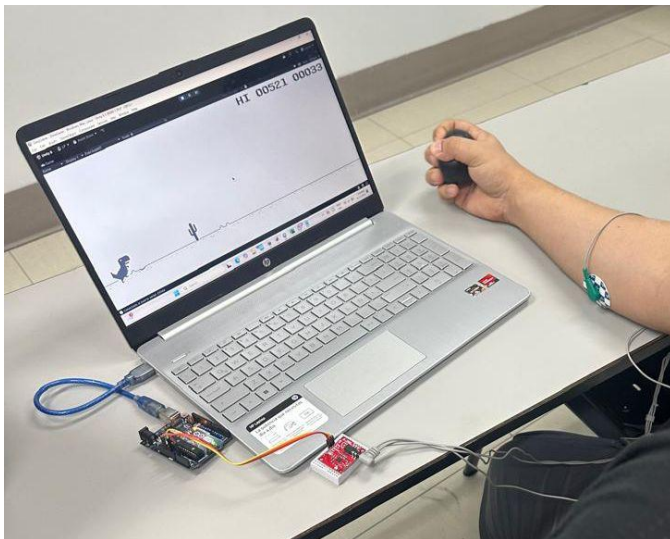


Fig. 6 Experimental setup showing complete system configuration during therapy session

G. System Operation Principle

The therapeutic interaction is based on a threshold detection mechanism rather than continuous EMG monitoring. During gameplay, the Arduino continuously reads EMG signals from the forearm muscles and maps them to the 0-140 range. When the mapped value exceeds the individually calibrated threshold, the corresponding action command is sent via serial port to Unity. Unity receives the command and executes the associated in-game action, providing immediate visual feedback that confirms successful muscle activation.

Importantly, no raw EMG data is stored or analyzed during gameplay—only threshold crossings are detected and translated into game commands. This approach minimizes computational load while maintaining therapeutic effectiveness through immediate visual feedback for successful muscle activations. The system operates in event-detection mode rather than continuous recording mode, making it suitable for real-time therapeutic applications where immediate feedback is crucial for motor learning and rehabilitation.

I. System Precision and Technical Performance

The system employs threshold-based detection with latency under 100 milliseconds, prioritizing real-time responsiveness over complex classification. While advanced EMG systems achieve 85-95% accuracy using machine learning [28], [29], the threshold approach ensures immediate feedback essential for motor learning. Individual calibration compensates for inter-subject variability, with system reliability evidenced by 85% maximum score achievement in Alien Attack. Performance variability in other games reflects movement complexity rather than detection failures [20], [30].

III. DESCRIPTION AND RESULTS

During the experimental phase, electromyographic (EMG) signals were recorded in real time using surface electrodes placed on the forearm muscles. These signals were used as commands to control tasks within the gamified therapeutic environment developed in the video games. Sessions were conducted with an average duration of 20 minutes per session.

Participants demonstrated varying performance levels across the three therapeutic games, reflecting different neuromuscular demands and skill requirements. Table III presents the complete score data.

The Alien Attack game demonstrated high accessibility, with 17 out of 20 participants 85% achieving the maximum score of 1000 points. The remaining participants scored 900 and 700 points respectively, still representing strong performance. This pattern suggests that the wrist flexion movements required for this game were within most participants' capabilities, making it suitable for early rehabilitation stages where building confidence and achieving success experiences are important.

Endless Runner presented significantly greater challenges, with scores ranging from 12 to 52 points. This limited score range and overall lower performance indicate higher demands for rapid alternating movements and precise timing. The game's design required participants to execute well-coordinated flexion-extension sequences with appropriate timing to navigate through obstacles successfully.

Dino Game showed intermediate difficulty, with scores ranging from 57 to 521 points. This variability suggests that wrist extension timing and coordination represented a moderate challenge for participants, with some demonstrating strong performance while others struggled with the precise timing required for obstacle avoidance.

TABLE III

INDIVIDUAL SCORES IN EMG-CONTROLLED THERAPEUTIC VIDEO GAMES

Participant (#)	Endless Runner	DinoGame	Alien Attack
1	30	521	1000
2	36	130	1000
3	19	90	1000
4	21	141	1000
5	38	120	1000
6	48	130	1000
7	23	175	700
8	12	57	1000
9	18	105	1000
10	20	170	1000
11	26	110	900
12	29	59	1000
13	38	68	1000
14	36	73	1000
15	42	89	1000
16	30	75	1000
17	45	95	1000
18	52	136	1000
19	35	82	1000
20	46	156	900

The system was evaluated with 20 healthy participants under controlled conditions. EMG signals were recorded before and after gameplay, and personalized activation thresholds were defined for each participant. Metrics such as RMS values before and after therapy, as well as video game performance, were analyzed to assess the impact of the intervention on neuromuscular activation. Results showed increases in EMG signals after therapy and improvements in video game performance, suggesting a positive impact on both neuromuscular activation and user motivation.

The project was validated by a Physiotherapist, who assessed the effectiveness of the system from a clinical and therapeutic perspective. According to the evaluation the system demonstrates strong future potential and broad clinical applicability; although technological precision could be further improved, its current performance is considered clinically pertinent and suitable for a wide range of patients.

In addition, a satisfaction questionnaire was administered at the end of the trials to evaluate user experience in terms of ease of use, perceived effectiveness, and motivation. The questionnaire results supported the system's viability, with high

scores in overall satisfaction and interest in continuing to use the system for future rehabilitation sessions as shown in Table IV. Participants particularly emphasized the system's accessibility, intuitive movement mapping, and absence of physical discomfort, along with its ability to provide active stimulation and clear functionality in rehabilitation.

TABLE IV

PORCENTAGE OF USER SATISFACTION IN THE QUESTIONNAIRE

Question	Score 5 (%)
Ease of Use	61.90
Stable Response	47.62
Response Time	57.14
No physical discomfort	85.17
Movement understanding	80.95
Active Stimulation	80.95
Maintained repetition	76.19
Functionality in rehabilitation	85.71

Results align with recent EMG-controlled rehabilitation research. User satisfaction (85.71% high functionality, 80.95% active stimulation) is consistent with Amin et al. (2025) who reported significant engagement improvements with EMG-feedback games [20]. Variable game difficulty (85% success in Alien Attack vs. 12-52 points in Endless Runner) reflects graduated therapeutic demands identified as critical for adherence [7], [10]. EMG signal amplitude increases post-gameplay corroborate findings from Seo et al. (2022) and Boulay et al. (2024) on neuromuscular coordination improvements [1], [11]. However, validation with clinical populations remains necessary to confirm therapeutic efficacy comparable to studies by Hohler et al. (2023) and Alyanak et al. (2025) [8], [31].

While the results are promising, several limitations should be noted. The study utilized a healthy participant sample, so further validation with clinical populations is necessary. The single-session design limits understanding of longitudinal effects, and the relatively small sample size (n=20) suggests caution in generalizing findings.

Future research should investigate long-term effects through multiple sessions, explore adaptation algorithms for automatic difficulty adjustment, and validate the system with clinical populations experiencing wrist mobility limitations. Additionally, incorporating more detailed EMG analysis during gameplay (while maintaining real-time performance) could provide deeper insights into neuromuscular adaptation patterns.

IV. CONCLUSIONS

This low-cost system (\$150–\$200 USD) addresses critical rehabilitation access gaps in Honduras and Latin America, where only 16% of accessibility studies originate despite a projected doubling of the elderly population by 2050. The 98% cost reduction versus commercial systems (€15,000–€20,000) [16] enables deployment in resource-limited settings where rehabilitation professional shortages are severe [32]. The Arduino-based design facilitates local adaptation and

maintenance, supporting WHO Rehabilitation 2030 goals for enhanced service coverage in underserved regions [19].

The developed system successfully demonstrated its clinical and technical effectiveness by enabling real-time control of therapeutic video games through EMG signals. The threshold-based detection mechanism, with latency under 100 milliseconds, ensured immediate and reliable translation of voluntary muscle contractions into game commands, a critical factor for motor learning and neuromuscular re-education. Notably, 85% of participants achieved the maximum score in Alien Attack, confirming that the system accurately captured wrist flexion activations and responded consistently across users with different neuromuscular profiles.

Beyond technical performance, the system proved effective in driving measurable therapeutic outcomes. Post-gameplay EMG recordings showed increases in signal amplitude compared to pre-session baselines, indicating enhanced neuromuscular activation as a direct result of the intervention. The progressive difficulty structure across the three games ensured that participants were continuously challenged at appropriate therapeutic levels, a design principle identified as essential for rehabilitation adherence and motor recovery [7], [10].

User validation further confirmed the system's effectiveness from both experiential and clinical perspectives. Satisfaction questionnaires yielded high scores in functionality for rehabilitation (85.71%), active stimulation (80.95%), and movement understanding (80.95%), reflecting that participants not only found the system usable but also perceived it as genuinely beneficial for their motor engagement. Clinical validation by a licensed Physiotherapist reinforced these findings, affirming that the system's performance is clinically pertinent and applicable to a wide range of patients.

Taken together, these results establish EMG-controlled video games as an effective, accessible, and motivating alternative to conventional rehabilitation therapies. The system successfully combines therapeutic functionality with patient engagement, addressing the critical limitations of repetitive and low-adherence traditional approaches. Future research should validate these outcomes with clinical populations, explore longitudinal effects across multiple sessions, and incorporate adaptive difficulty algorithms to further personalize and optimize the therapeutic experience.

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