Academic Journal of Engineering and Technology Science
ISSN 2616-5767 Vol.9, Issue 2: 37-44, DOI: 10.25236/AJETS.2026.090205

Gamified Interactive Bilateral Full-Range Upper-Limb Rehabilitation Trainer

Zhichen Guan[a]

BASIS International School Guangzhou, Guangzhou, China
[a]116860bigz@basischina.com

Abstract: *This study addresses upper-limb dysfunction caused by neurological diseases such as stroke, as well as the limitations of traditional rehabilitation devices, which are often bulky, complex, and poorly accessible for home use. A bilateral upper-limb rehabilitation device is developed to provide a practical solution for home-based therapy. The system is designed using Fusion 360 and integrates an aluminum base, a servo-driven mechanism, and Arduino-based control. It supports circular, rectangular, and personalized game-based interactive training modes, enabling bilateral coordinated rehabilitation. The proposed device is compact and portable, making it suitable for independent use in home environments. Through multiple rounds of experimental testing, the system demonstrates stable motion control, high operational reliability, consistent movement execution, and safety performance. Compared with unilateral rehabilitation systems, the bilateral design enhances inter-hemispheric coordination training, improves patient engagement, and increases rehabilitation compliance. The device shows both clinical value and practical application potential, providing an efficient and enjoyable solution for home-based rehabilitation. Future work will further personalize and optimize the system to meet the needs of different patient groups.*

Keywords: *upper-limb rehabilitation device, bilateral training, interactive training, personalized rehabilitation*

1. Introduction

Despite continuous advances in medical technology, stroke still has a profound impact on patients. Approximately 80% of stroke survivors suffer from upper-limb dysfunction, and many continue to exhibit significant motor deficits six months after onset, severely limiting daily activities and independence [1]. Conventional rehabilitation is often insufficient to address these impairments, creating a need for advanced, quantifiable, and highly repetitive training strategies.

Studies indicate that bilateral upper-limb training devices offer clear advantages in functional recovery, outperforming unilateral training in improving coordination and promoting neural plasticity [2][3]. In recent years, robot-assisted rehabilitation has emerged as an important approach due to its high repeatability and quantitative evaluation capability.

International research on hemiplegic upper-limb recovery now focuses on bilateral robot-assisted training and its underlying mechanisms. Tang [4] applied a bilateral robotic training system to chronic stroke patients and investigated changes in neural functional connectivity using quantitative EEG (Figure 1). The results showed that, compared with conventional therapy, bilateral robotic training significantly improved upper-limb motor performance and enhanced interhemispheric cortical connectivity, demonstrating its positive role in neural network reorganization.

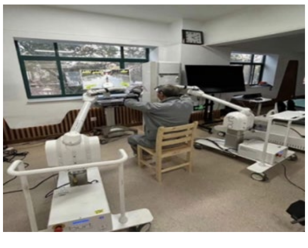


Figure 1 Bilateral Rehabilitation Training Diagram

An MDPI research team compared unilateral (URT) and bilateral robot-assisted training (BRT) [5].

The results indicated that the BRT group achieved higher Fugl–Meyer upper-limb scores and better daily activity performance, highlighting the advantages of bilateral coordination.

Recent studies integrate bilateral robotics with mirror therapy and biofeedback. Zhou [6] proposed a robot-assisted mirror rehabilitation framework in which movements of the healthy limb serve as driving signals to control symmetric motion of the affected side, combined with surface EMG feedback to enhance user participation and personalized adaptation. Zhang [7] developed a system combining mirror visual feedback with robotic actuation, mapping the healthy limb motion to guide the affected limb. Multi-cycle interventions significantly improved joint range of motion, fine motor skills, and motor cortex activation. Kim [8] further integrated a robotic glove with mirror therapy, enabling subacute stroke patients to perform grasping and extension training, providing a new technical pathway for bilateral hand rehabilitation.

Aramaki et al. [9] (2011) conducted an early study on the application of bilateral robot-assisted rehabilitation training in patients with subacute stroke. Their work was based on a four-degree-of-freedom arm robot designed to provide training intervention for patients with severe hemiplegia. The results showed that bilateral robotic training not only increased the range of motion of the affected limb but also significantly improved fine motor skills of the fingers, further verifying the clinical effectiveness of bilateral robotic rehabilitation.

Hwang et al. [10] integrated bilateral training with virtual reality (VR) technology, for example by using tablet computers and inertial sensors (IS) to perform interactive motor-task exercises. This approach enhanced movement coordination and patient engagement, thereby improving the overall rehabilitation experience.

In addition, Wu [11]. conducted a randomized controlled trial comparing unilateral robot-assisted training (URT) and bilateral robot-assisted training (BRT) on upper extremity and trunk function in stroke patients. The study found that BRT produced greater reductions in compensatory trunk movement and differential improvements in upper limb/trunk performance compared with URT, highlighting distinct benefits of bilateral training strategies.

2. Mechanical Structure Design

The concept for developing the bilateral upper-limb rehabilitation device originated from the author’s volunteer experience in age-friendly communities. Field investigations showed that upper-limb dysfunction in elderly stroke and hemiplegic patients affects daily independence more directly than lower-limb impairment. Therefore, this study is community-oriented and focuses on upper-limb recovery by designing a bilateral cooperative training device aimed at a compact and portable system suitable for home and community use.

The actuator is the core component of motion control in the device. Compared with DC motors, which have high speed but large inertia and low positioning accuracy, servo motors are more suitable for rehabilitation training requiring safety and repeatability. Therefore, this study employs Hiwonder serial metal single- and dual-axis 20 kg high-precision servos as the driving units. These servos provide high torque, durable metal gears, and angle feedback, enabling precise PWM-based position control and supporting reliable trajectory planning and bilateral synchronized motion.

During the initial structural design stage, modeling was first conducted based on commonly used anthropometric parameters reported in the literature, and acrylic plates were selected for the base and linkages to reduce manufacturing complexity. A modular design approach was adopted, and Autodesk Fusion 360 was used to model the base, shafts, gears, connecting rods, and top handle, with the overall layout completed through extrusion, cutting, mirroring, patterning, and dimensional constraints. After the initial prototype was completed, shafts, sleeves, and gears were fabricated using 3D printing, while the acrylic base and links were processed with an L-shaped cutter and assembled from the bottom upward. The initial design is shown in Figure. 2 and 3.

Figure 2 Early-Stage Unilateral Diagram

Figure 3 Early-Stage Bilateral Diagram

Testing of the initial prototype showed that the acrylic structure underwent slight deformation under training loads, resulting in insufficient long-term stability. In addition, servo loads increased near extreme joint angles, posing potential safety risks, and the compact layout limited bilateral coordinated motion.

To address these issues, several improvements were implemented in the final design. First, the base and main load-bearing links were replaced with aluminum alloy to enhance stiffness and durability. Second, based on anthropometric data of Asian populations, link lengths and joint ranges were recalibrated, setting the effective upper-limb length to approximately 300 mm and both L2 and L3 to 100 mm, with a 10-15% safety margin reserved in angle control to avoid extreme positions. Finally, the base dimensions were re-planned to remain within one foot, improving portability and suitability for home and community use.

In the final design, a second contralateral mechanism was fabricated following the initial assembly procedure to achieve a bilaterally symmetric layout. Ergonomic handles were installed at both end-effectors to improve grip stability and user comfort during training. Compared with the initial prototype, the optimized bilateral rehabilitation device exhibits clear improvements in range of motion, structural stability, and load capacity. The final assembled structure is shown in Figure. 4-7.

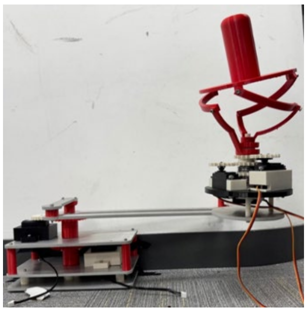


Figure 4 Overall Diagram

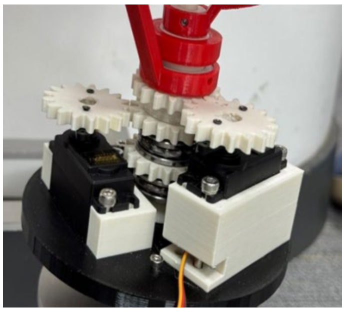


Figure 5 Detailed View Diagram

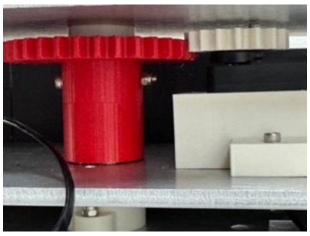


Figure 6 Detailed View Diagram

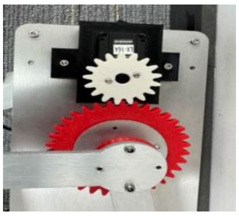


Figure 7 Detailed View Diagram

3. Hardware Design

3.1 Electronic Design Proposal

After completing the mechanical structure design, the core task is to achieve stable and precise servo actuation through a hierarchical control architecture. The system adopts a layered configuration of “computer–control board–servo controller–actuator.”

The servos are connected to a dedicated servo controller, which centrally manages power supply and signal distribution. The servo controller communicates with the main PCB board via crossed serial connections (TX to RX, RX to TX, with a common GND), and is powered by an external 12 V lithium battery to ensure stable operation under load conditions.

The PCB board is directly interfaced with an Arduino Nano (RX/TX/GND connected correspondingly). The Nano converts motion commands into servo control signals and connects to the computer via USB for program uploading, parameter configuration, and real-time status monitoring. The serial monitor on the computer provides feedback on system operation.

To extend wrist rehabilitation functionality, a parallel-ball actuator module is connected to a second Arduino Nano, powered independently and operated under dedicated control logic to enable targeted wrist training.

3.2 Hardware Connection Diagram

The system is divided into two connection sections: the left part corresponds to the upper-arm linkage, and the right part corresponds to the forearm linkage, as illustrated in Figure 8.In the main robotic arm below, the Arduino Nano development board serves as the main controller, responsible for communicating with both the computer-side game interface and the motor driver. Different modes are switched via a single button; the motion mode is activated by default upon startup, where the device drives the upper limb to move. When the button is pressed, it enters the game interaction mode, allowing the snake in the game interface to be controlled through manual movement, with score recording and adjustable motion status supported.

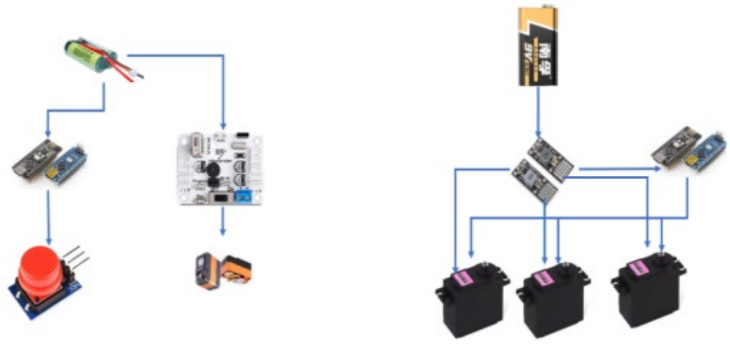


Figure 8 Hardware Connection Diagram

4. Control System

4.1 Software Design

In software control, as shown in Figure. 9, servo motion planning adopts a chain-based trajectory generation method. A unified center coordinate is defined for the motion path and radius to determine target positions in space, and angles θ1and θ2 are calculated using the equations in Formula. 1. Parameters a, b, and c are obtained from Formula. 2, where L1=300 mm and L2=L3=100 mm. The angles are converted from degrees to radians and mapped into control commands within a 0-1000 range to drive the servos along the planned trajectory. In the Arduino environment, the control process consists of initialization and loop execution. Coordinate parameters, servo objects, link lengths, and functions are defined first, while communication checking and hardware initialization are completed in the setup function. The loop function then periodically updates target coordinates and outputs commands to achieve continuous trajectory execution. Any abnormal operation is reported via the serial monitor to ensure reliability and maintainability.

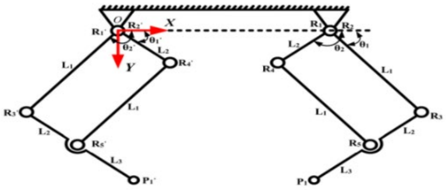


Figure 9 Chain Design Diagram

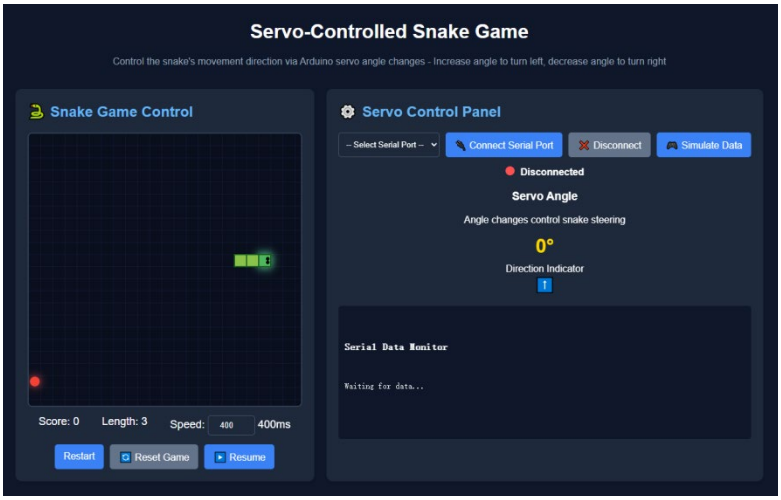
$$\begin{cases} \theta_1 = 2\tan^{-1}\left(\dfrac{-b_1 + i_1\sqrt{b_1^2 - 4a_1c_1}}{2a_1}\right) \\ \theta_2 = 2\tan^{-1}\left(\dfrac{-b_2 + i_2\sqrt{b_2^2 - 4a_2c_2}}{2a_2}\right) \end{cases} \tag{1}$$

$$\begin{aligned} a_1 &= x^2 + y^2 + L_1^2 - (L_2 + L_3)^2 + 2xL_1 \\ b_1 &= -4yL_1 \\ c_1 &= x^2 + y^2 + L_1^2 - (L_2 + L_3)^2 - 2xL_1 \end{aligned} \tag{2}$$

4.2 Program Design

The program is implemented on the Arduino platform to achieve intelligent dual-servo control following an “initialization–main loop–state-driven” framework. During initialization, serial communication is set to 9600 bps, the touch sensor pin (Pin 2) is configured as an input, and an angle–position mapping is used to calculate the 90° home position, with delay calibration performed to reset both servos accurately. After entering the main loop, a 200ms debounce mechanism is applied to detect touch input. When a valid touch is triggered, the system switches its state: if it is in the motion sequence mode, it transitions to the unloading mode and releases servo torque; if it is in the unloading mode, it returns to the motion mode and resets all motion parameters. If no touch is detected, the motion mode executes a predefined eight-step sequence by means of segmented interpolation to generate smooth servo movements (following the “increase–reset–decrease–reset” logic), while the unloading mode periodically monitors and outputs real-time servo positions every 500ms, thus enabling rapid and reliable state switching.

The servo communication function is encapsulated via a Servo Controller class, and a state-machine strategy is adopted to decouple motion and unloading behaviors. This forms a closed-loop control structure that integrates calibration, detection, state driving, and real-time feedback (Figure 10). Figure 11 presents a human-machine interaction (HMI) interface designed for gamified rehabilitation training, featuring an enhanced real-time feedback mechanism to improve user engagement.


Servo-Controlled Snake Game

Control the snake's movement direction via Arduino servo angle changes - Increase angle to turn left, decrease angle to turn right

Snake Game Control

Score: 0
Length: 3
Speed: 400 400ms

Servo Control Panel

Disconnected

Servo Angle

Angle changes control snake steering

0°

Direction Indicator

```
Serial Data Monitor

Waiting for data...
```

Figure 10 Human-Machine Interactive Interface Design

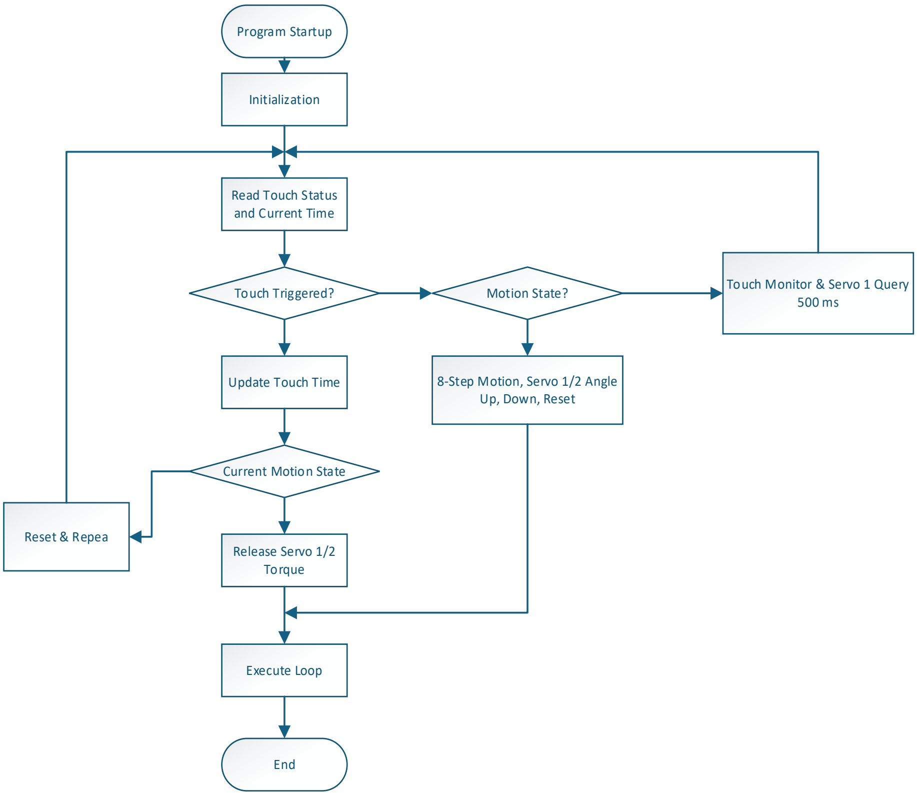


Figure 11 Program Flowchart

5. Experimental Measurement

5.1 Experiment 1: Independent Handle Motion and Position Test

This experiment aims to verify the motion accuracy, response speed, and repeatability of the independent handle module in the bilateral upper-limb rehabilitation device to ensure safe and effective training. Pre-integration testing and repeated power-cycling validation are conducted to eliminate random errors and confirm system reliability over multiple operation cycles, providing support for subsequent bilateral control and rehabilitation strategies. The experimental setup is shown in Figure. 12.

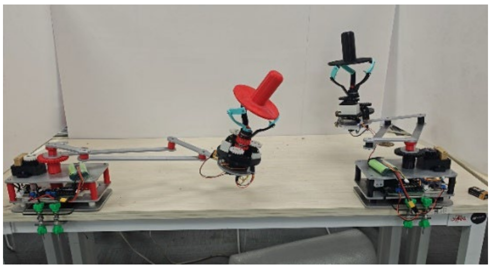
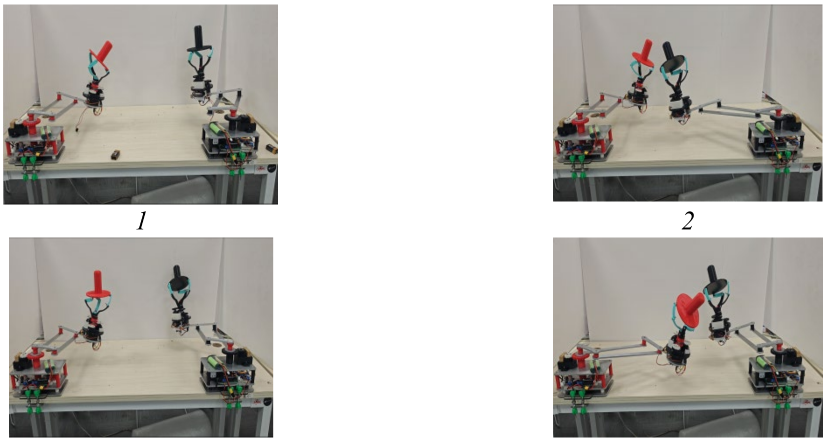


Figure 12 Controller Button Layout Diagram

Across five trials, the handle module achieved a 100% successful power-on initialization rate. The "left swing–right swing–rotation" motion cycle was smooth and correctly sequenced without stalling, meeting the design requirements.

5.2 Experiment 2: Upper-Arm Position and Motion Test

This experiment evaluates the position control performance and operational safety of the upper-arm actuator in the bilateral rehabilitation device by testing motor and sensor reliability, motion continuity, and homing accuracy. Repeated trials are conducted to analyze system stability, providing a basis for subsequent cooperative control, trajectory planning, and safe human–robot interaction design, as shown in Figure. 13.



1 *2*

3 *4*

Figure 13 Upper Arm Test Diagram

Across five trials, the upper-arm module responded within 3s after power-on, returned to the home position with an error of less than 10 mm, and showed no jamming or abnormal noise, indicating good motion coordination.

5.3 Experiment 3: precise motion time measurement

This experiment quantitatively evaluates the time response and cycle stability of the motion modules in the bilateral upper-limb rehabilitation device. By precisely measuring the motion cycle duration of the handle and robotic arms and analyzing repeated trials with timing calibration, system consistency is assessed to support parameter tuning and synchronization optimization, ensuring safe and comfortable rehabilitation use. The test results are as follows table1:

Table 1: Motion time data recording.

Motion Cycle Test Data of the Left Robotic Arm		**Motion Cycle Test Data of the Right Robotic Arm**		**Motion Cycle Test Data of the Handle Module**	
Number of Tests	Duration(s)	Number of Tests	Duration(s)	Number of Tests	Duration(s)
1	37.02	1	28.15	1	15.10
2	36.15	2	27.20	2	16.20
3	37.20	3	27.35	3	15.35
4	38.10	4	28.05	4	15.25
5	36.53	5	29.25	5	16.10
Mean	**36.80**	Mean	**27.80**	Mean	**15.40**

The tested single-side upper-arm actuator and handle control module of the bilateral upper-limb rehabilitation device fully comply with the predefined design specifications, particularly in three core performance dimensions: functional integrity (i.e., complete realization of preset motion modes such as circular, rectangular, and game-based interactive training, as well as accurate execution of control logic), motion coordination (smooth synchronization between joint movements, consistent response to servo control signals, and no lag in bilateral collaborative motion), and cycle stability (stable operational performance across five rounds of repeated experimental testing with negligible deviation in motion parameters). Throughout the testing process, the modules exhibited no operational anomalies including mechanical stalling under training loads, motion overshoot beyond the safe angle range (with the 10-15% safety margin effectively maintained), or logical mis-operation of control commands. These reliable performance characteristics not only validate the rationality of the mechanical structure optimization and electronic control design but also lay a solid technical foundation for the subsequent integration of the bilateral symmetric full-system. By ensuring the stability and safety of key functional components, the modules guarantee that the integrated bilateral rehabilitation device can meet the practical application requirements of home and community-based rehabilitation, providing users with a safe, consistent, and effective upper-limb training tool.

6. Conclusion

The bilateral upper-limb rehabilitation robot project has made notable progress in promoting community- and home-based rehabilitation robotics. Through integrated design of mechanical structure, drive control, and human-machine interaction, a compact, portable robotic prototype was developed to safely enable bilateral coordinated training, significantly enhancing the controllability, adaptability, and patient compliance of upper-limb rehabilitation for hemiplegics. A key feature is its gamified training modes (e.g., circular, rectangular, and personalized interactive games like the servo-controlled snake game), which transform repetitive exercises into engaging experiences to boost long-term adherence. The prototype’s core advantages include an innovative bilaterally symmetric, modular, and ergonomically optimized structure, high-precision servo-driven actuation with real-time feedback, and balanced robustness and cost-effectiveness—all addressing the limitations of traditional bulky, complex devices. It effectively bridges professional therapy and at-home training, demonstrating substantial clinical value and practical application potential.

Future work will focus on further personalizing and optimizing the system, such as refining training modes for varying degrees of upper-limb dysfunction, expanding gamified interactive scenarios, and adapting mechanical and control designs to individual patient characteristics and rehabilitation progress, to deliver more targeted home-based rehabilitation solutions.

References

[1] Simkins, M., Kim, H., Abrams, G., Byl, N., & Rosen, J. (2013). Robotic unilateral and bilateral upper-limb movement training for stroke survivors afflicted by chronic hemiparesis. IEEE ... International Conference on Rehabilitation Robotics : [proceedings], 2013, 6650506.
[2] van Delden, A. L., Peper, C. L., Kwakkel, G., & Beek, P. J. (2012). A systematic review of bilateral upper limb training devices for poststroke rehabilitation. Stroke research and treatment, 2012, 972069.
[3] Wongwatcharanon, T., Earde, P. T., Rungroungdouyboon, B., & Kooncumchoo, P. (2025). Improving Upper-Limb Recovery in Patients with Chronic Stroke Using an 8-Week Bilateral Arm-Training Device. Life, 15(7), 994.
[4] Tang, C., Zhou, T., Zhang, Y., Yuan, R., Zhao, X., Yin, R., Song, P., Liu, B., Song, R., Chen, W., & Wang, H. (2023). Bilateral upper limb robot-assisted rehabilitation improves upper limb motor function in stroke patients: a study based on quantitative EEG. European journal of medical research, 28(1), 603.
[5] Yuan, R., Qiao, X., Tang, C., Zhou, T., Chen, W., Song, R., Jiang, Y., Reinhardt, J. D., & Wang, H. (2023). Effects of Uni- vs. Bilateral Upper Limb Robot-Assisted Rehabilitation on Motor Function, Activities of Daily Living, and Electromyography in Hemiplegic Stroke: A Single-Blinded Three-Arm Randomized Controlled Trial. Journal of Clinical Medicine, 12(8), 2950.
[6] Chen, J., Cheng, Z., Cai, Y., Zhang, S., Zhu, C., & Zhang, Y. (2025). Robot-Assisted Mirror Rehabilitation for Post-Stroke Upper Limbs: A Personalized Control Strategy. Sensors, 25(18), 5659.
[7] Qian, J., Liang, C., Liu, R., Yu, J., Yang, T., & Bai, D. (2025). Combination of robot-assisted glove and mirror therapy improves upper limb motor function in subacute stroke patients: a randomized controlled pilot study. Frontiers in neurology, 16, 1602896.
[8] Li, S., Zhang, J., Xu, Y., & Yang, Y. (2026). Robot-Assisted Mirror Therapy for Upper Limb and Hand Recovery After Stroke: Clinical Efficacy and Insights into Neural Mechanisms. Journal of clinical medicine, 15(1), 350.
[9] ARAMAKI, S., SAYAMA, I., NAKAZAWA, M., YOKOYAMA, E., SHIMOMURA, T., & HOSOKAWA, K. (2011). Robot Development and the Effect of Robot-aided Bilateral Training of Hemiplegic Upper Limbs in Subacute Stroke Patients: A Randomized Controlled Trial. The Japanese Journal of Rehabilitation Medicine, 612-622.
[10] Hwang, T. H., Boltzmann, M., Jenner, S. B., Rollnik, J. D., Schmitz, G., & Effenberg, A. O. (2025). A Novel Bilateral Upper Limb Training Method for Stroke Rehabilitation. IEEE transactions on neural systems and rehabilitation engineering : a publication of the IEEE Engineering in Medicine and Biology Society, 33, 4184–4195.
[11] Wu, C. Y., Yang, C. L., Chen, M. D., Lin, K. C., & Wu, L. L. (2013). Unilateral versus bilateral robot-assisted rehabilitation on arm-trunk control and functions post stroke: a randomized controlled trial. Journal of neuroengineering and rehabilitation,10(1), 35.