

Design, Manufacturing, and Testing of a Continuous Passive Motion Transmission Mechanism

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(Received January 29, 2026; accepted September 14, 2026)

Keywords: total hip arthroplasty, continuous passive motion, flexion, abduction, transmission mechanism design.

In this study, we present the development of a smart, dual-axis continuous passive motion (CPM) rehabilitation device for patients undergoing total hip arthroplasty. Most commercial CPM systems provide only uniaxial flexion–extension motion, limiting their application in comprehensive hip rehabilitation. The proposed system introduces an additional abduction mechanism to enable multidirectional movement during postoperative recovery. The mechanical structure adopts a modular design that allows an independent assembly of the flexion and abduction modules. A programmable logic controller (PLC)-based electrical control unit integrated with a human–machine interface (HMI) was developed for coordinated dual-axis operation. Four endpoint position sensors were installed at the 0 and 90° limits of the flexion module and the 0 and 30° limits of the abduction module. Intermediate positions are controlled by the PLC according to the stepper-motor pulse count and linear-actuator stroke, while the endpoint position sensors provide origin confirmation, travel-limit detection, and overtravel protection. Under abnormal overtravel conditions, the PLC stops the corresponding motion and displays a warning on the HMI. Functional testing confirmed smooth and stable dual-axis operation. These results demonstrate the feasibility of the proposed system and indicate greater motion versatility and integrated control functionality than conventional single-axis CPM configurations, supporting its potential for future clinical application.

1. Introduction

Yoon *et al.* reported that population aging poses a growing healthcare burden worldwide, with hip fractures increasingly prevalent among elderly individuals because of degenerative changes or accidental falls.⁽¹⁾ More than 90% of hip fractures occur in people aged 65 years or

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<https://doi.org/10.18494/SAM6250>

older, often leading to long-term mobility impairment. To restore hip function, total hip arthroplasty has become a standard surgical intervention. However, early-stage rehabilitation remains a critical factor for regaining the range of motion (ROM) and improving postoperative outcomes.^(2–4)

Continuous passive motion (CPM) therapy plays an essential role in early rehabilitation by providing slow and consistent limb movement that prevents stiffness and promotes joint recovery.⁽⁵⁾ Nevertheless, most commercial CPM systems provide only uniaxial flexion–extension motion, which is insufficient for comprehensive hip rehabilitation. The lack of abduction training restricts lateral stability and delays the recovery of the hip abductor muscles—key components of gait balance.⁽⁶⁾

Recent advances in robotic and wearable rehabilitation technologies, such as the Hybrid Assistive Limb and adaptive exosuits, have introduced new possibilities for motion-assisted recovery.^(2,5–7) These systems integrate soft actuators, adaptive oscillators, and lightweight exoskeletal frames to support human locomotion and muscle activation.^(7–9) However, they remain costly, heavy, and difficult to operate, limiting their accessibility for clinical and home-based rehabilitation.

In addition to mechanical improvements, electrical control systems based on the programmable logic controller (PLC) and human–machine interface (HMI) have been increasingly adopted in medical robotics to ensure motion control, synchronization, and operational safety.⁽¹⁰⁾ The integration of PLC–HMI architecture enhances control accuracy and allows the intuitive adjustment of parameters such as speed, range, and repetition cycles, thereby improving usability and reducing setup complexity for clinical operators.

Recent studies have further demonstrated the growing application of lower-limb robotic exoskeletons in rehabilitation, with improvements reported in walking performance and lower-limb motor function following robot-assisted training.^(11,12)

In the proposed CPM system, mechanical sensing is implemented using four endpoint position sensors. Two sensors are installed at the 0 and 90° limits of the flexion module, and two sensors are installed at the 0 and 30° limits of the abduction module. These sensors are used for origin detection, maximum travel limitation, and overtravel protection. When an endpoint sensor is activated, the signal is transmitted to the PLC, which stops or reverses the corresponding motion according to the programmed sequence. If an abnormal operating condition is detected, an alarm message is displayed on the HMI. Therefore, the sensing application in this study focuses on endpoint position detection, travel-limit detection, and overtravel protection.

Therefore, there is a continuing demand for a lightweight, user-friendly, and dual-axis CPM system capable of providing both flexion and abduction motions with coordinated control and safety functions. To address these limitations, in this study, we present the design, manufacturing, assembly, and functional verification of a smart dual-axis CPM rehabilitation device. The system introduces an independent abduction module capable of up to 30° of lateral motion, supplementing conventional flexion–extension rehabilitation to enhance hip-joint stability and restore natural gait.

The mechanical design adopts a modular structure, allowing the flexion and abduction modules to operate independently or in synchronization. The manufacturing process employs

precision machining and laser cutting to ensure accuracy and repeatability. Each component is assembled using alignment connectors to guarantee precise positioning and facilitate maintenance.

An electrical control unit based on the PLC and HMI was developed to support motion control and user interactivity. The HMI enables the intuitive adjustment of motion parameters—including angle, speed, and range—while the PLC coordinates the operation of the flexion and abduction modules. This integration simplifies therapist interaction and allows patients to safely perform rehabilitation training.

Overall, this study provides a comprehensive framework that integrates mechanical and electrical design to realize a reliable dual-axis CPM rehabilitation system. The following sections describe the system design, fabrication process, experimental testing, and control implementation in detail, demonstrating the practical potential of the developed device for clinical rehabilitation applications.

2. Materials and Methods

In this study, a smart dual-axis CPM rehabilitation device was developed for postoperative hip rehabilitation. The research process consisted of five stages: mechanical design, component manufacturing, structural assembly, functional testing, and electrical control system integration (Fig. 1).

2.1 System design

The dual-axis CPM rehabilitation device was developed on the basis of the principles of modularity, ergonomic safety, and structural balance. The design emphasizes independent motion modules for flexion and abduction, which can be easily configured or synchronized to meet various rehabilitation needs. A modular framework was adopted to simplify assembly, calibration, and maintenance while enhancing system reliability. The mechanical layout follows natural hip joint kinematics to ensure smooth and comfortable limb movement. Lightweight aluminum alloy and stainless steel were selected to achieve a balance among rigidity, durability, and portability.

In the flexion mechanism, θ denotes the included angle between the centerlines of the linkage members, as shown in Fig. 2. This geometric linkage angle describes the configuration of the transmission mechanism and is distinct from the hip flexion angle used to define the rehabilitation range. In this study, the hip flexion angle ranged from 0 to 90°.

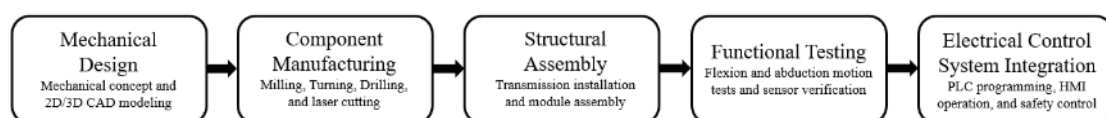


Fig. 1. Five-stage development process of dual-axis CPM rehabilitation system.

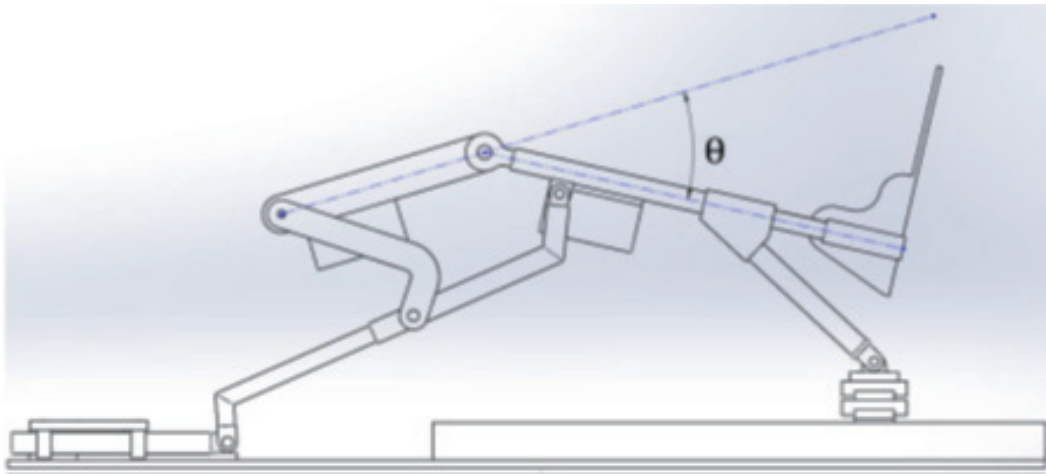


Fig. 2. (Color online) Definition of the linkage angle θ in flexion transmission mechanism.

To visualize the design concept and verify mechanical alignment, both 2D and 3D computer-aided design (CAD) models were created. The 2D layout was used to define linkage geometry, actuator placement, and the range of motion (Fig. 3), whereas the 3D model illustrated the modular framework and ergonomic configuration (Fig. 4). These CAD models helped optimize weight distribution, operating range, and overall structural stability, providing both precision and comfort during rehabilitation training.

2.2 Manufacturing and assembly

The overall fabrication and assembly process consists of six main stages: material preparation, machining, part finishing, transmission installation, module assembly, and system integration. These stages are summarized in the flow diagram shown in Fig. 5.

All structural components of the dual-axis CPM rehabilitation device were fabricated using conventional machining and cutting processes, including milling, turning, drilling, and laser cutting (Fig. 6). These processes were employed to ensure dimensional accuracy and repeatability across all mechanical parts. The major components include side frames, support brackets, lead-screw housings, linkage arms, and actuator mounts, which were manufactured from aluminum alloy and stainless steel to provide sufficient strength and corrosion resistance (Fig. 7).

During fabrication, machining operations were performed on a milling machine, lathe, and drilling machine, whereas laser cutting was used for the high-precision contouring of the frame plates and base panels. After individual parts were completed, all components were deburred, aligned, and visually inspected to verify dimensional consistency.

The assembly stage involved the sequential installation of the transmission mechanism, actuator linkage, and base frame (Fig. 8). Each motion module—flexion and abduction—was first preassembled and then integrated into the main structure using alignment connectors to

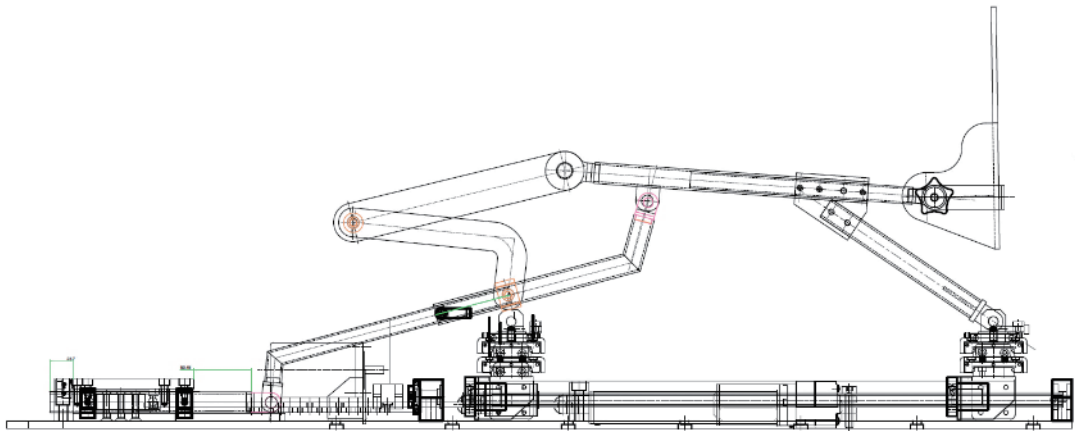


Fig. 3. (Color online) 2D CAD layout of dual-axis CPM rehabilitation device.

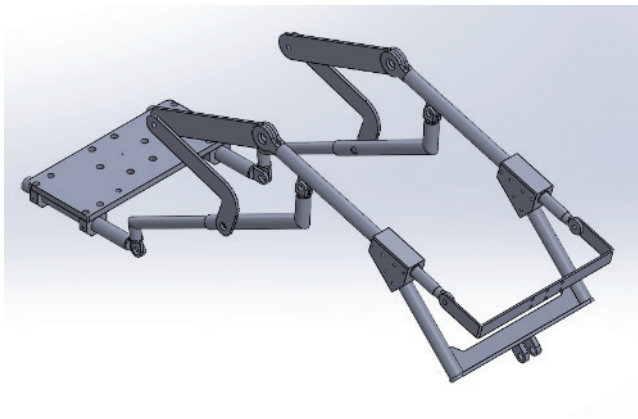


Fig. 4. (Color online) 3D CAD model illustrating the modular structure and ergonomic configuration of the system.

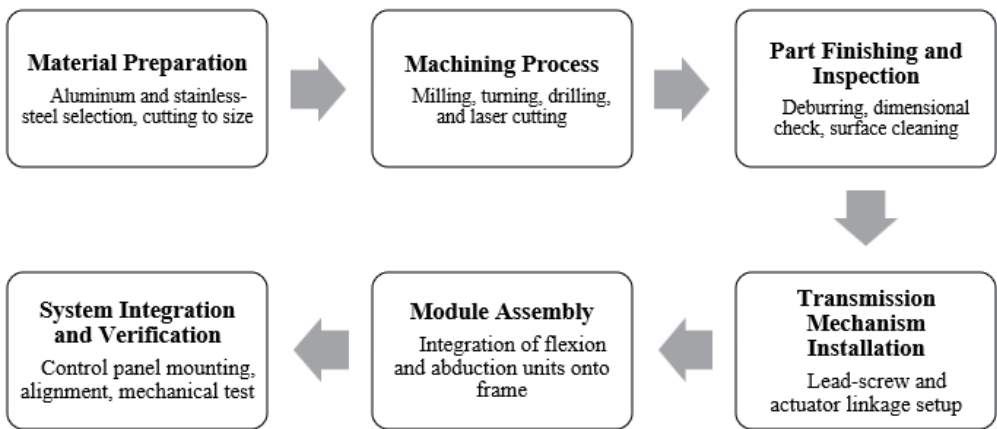


Fig. 5. Manufacturing and assembly process flow of the dual-axis CPM rehabilitation device.

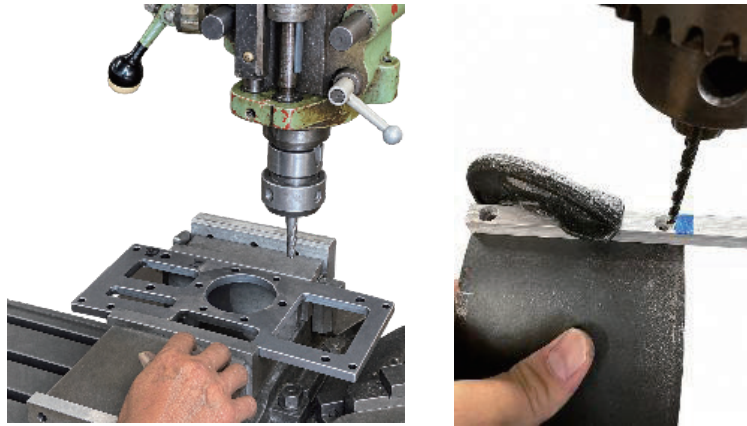


Fig. 6. (Color online) Machining process of structural components.

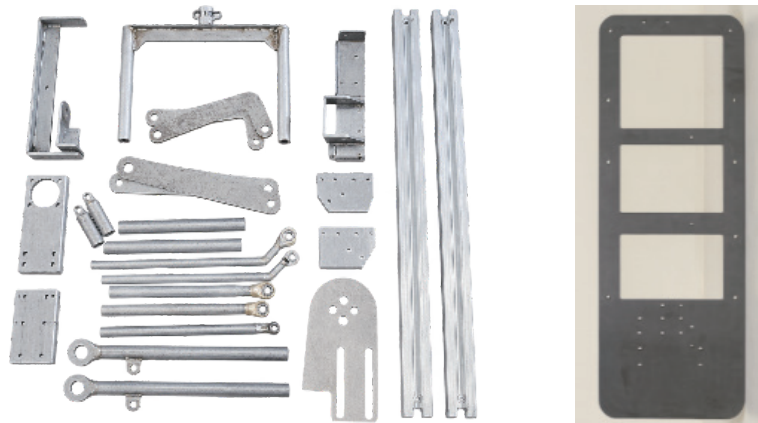


Fig. 7. (Color online) Fabricated components of dual-axis CPM rehabilitation device, showing laser-cut frame plates, linkage arms, brackets, and base parts before assembly.

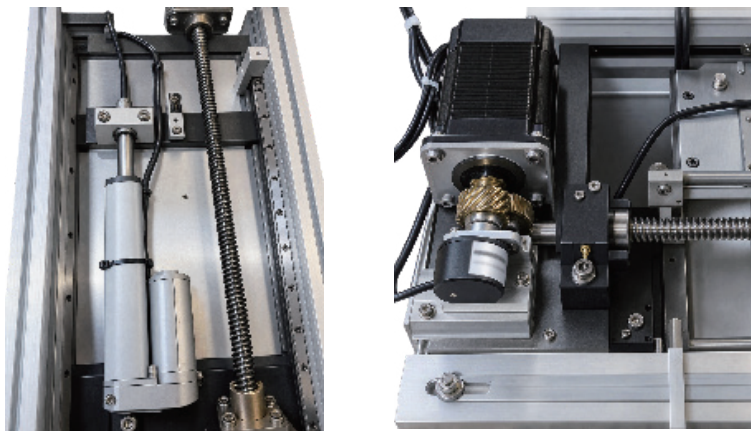


Fig. 8. (Color online) Installation of transmission mechanism.

ensure accurate positioning and smooth motion transmission. The electrical control panel and interface mounting plate were also fixed onto the front frame for easy access and wiring arrangement.

2.3 Functional testing

Functional testing was performed to verify the operational performance of the developed dual-axis CPM device. The purpose of the tests was to confirm the smoothness, stability, and coordination of both flexion and abduction movements under simulated rehabilitation conditions.

During the test, a simulated leg was placed on the CPM support platform to replicate the actual patient posture during hip joint rehabilitation (Fig. 9). The hip flexion angle was controlled from 0 to 90°, while the abduction angle was controlled from 0 to 30°. The four endpoint position sensors were also tested during operation. The flexion sensors were activated at the 0 and 90° motion limits, whereas the abduction sensors were activated at the 0 and 30° motion limits. The activation of each sensor transmitted a limit signal to the PLC, which stopped or reversed the corresponding motion according to the programmed sequence. The HMI alarm function was additionally verified under simulated abnormal overtravel conditions. The observed operation confirmed smooth and stable dual-axis motion without observable mechanical interference, supporting the mechanical feasibility and operational safety of the developed prototype.

2.4 Electrical control and HMI operation

To support coordinated motion control and enhance user interactivity, an electrical control system was developed on the basis of the PLC integrated with the HMI. The PLC serves as the main control unit, coordinating the flexion and abduction modules according to the programmed motion sequence.

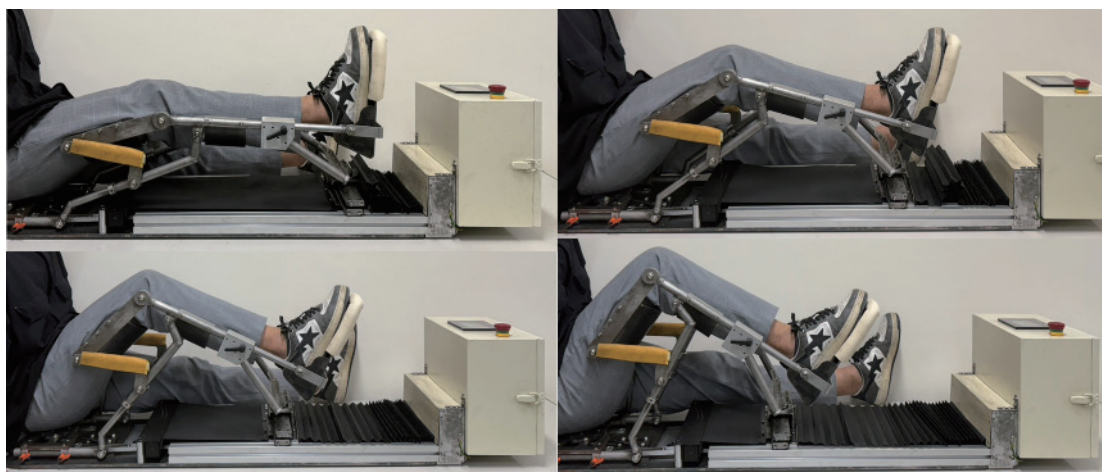


Fig. 9. (Color online) Functional testing setup and simulated leg placement on CPM device for flexion and abduction evaluation.

Operator-defined parameters are entered through the HMI and transmitted to the PLC, as summarized in the electrical control architecture (Fig. 10). For the flexion module, the PLC sends pulse and direction commands to the stepper motor driver, which drives the stepper motor and lead-screw mechanism. The abduction module is controlled through the PLC output and linear actuator control circuit. Endpoint sensor and emergency-stop signals are transmitted to the PLC as safety inputs for travel-limit detection and operational protection. The emergency-stop function allows the operator to immediately terminate actuator motion when an abnormal operating condition is observed.

Intermediate hip flexion angles are determined from the pulse count of the stepper motor, whereas intermediate abduction positions are determined from the programmed stroke of the linear actuator. The four endpoint sensors provide initial-position confirmation, travel-limit detection, and overtravel protection for the flexion and abduction modules. The HMI provides

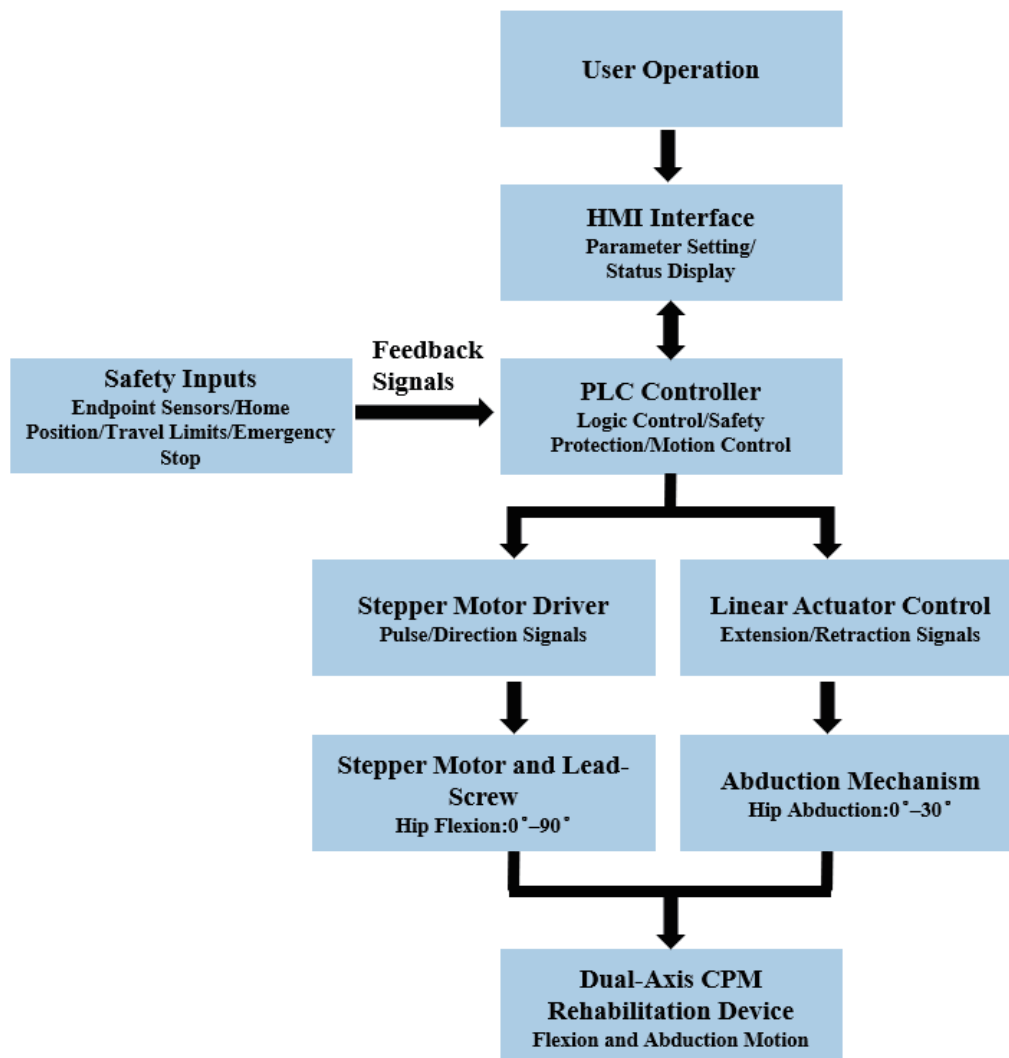


Fig. 10. (Color online) Simplified electrical control architecture and signal flow of dual-axis CPM rehabilitation system.

an intuitive touchscreen interface that allows operators to set parameters such as flexion and abduction angles, motion speed, and operation mode (Fig. 11). The system supports both the manual mode, for real-time motion adjustment, and the continuous mode, for repetitive rehabilitation training.

All electronic components—including the PLC, motor drivers, relays, and power supply—were installed inside a front-mounted control cabinet for convenient access and maintenance (Fig. 12).

3. Results and Discussion

In this section, we present the performance and operational results of the developed dual-axis CPM rehabilitation device. The discussion follows the same sequence as the development process, including system design, manufacturing and assembly, functional testing, electrical control operation, and certification evaluation.

The CPM device integrates two independent motion modules for flexion and abduction, coordinated by the PLC and HMI. The results confirm stable dual-axis motion and reliable control operation, demonstrating the device's potential for postoperative hip rehabilitation.

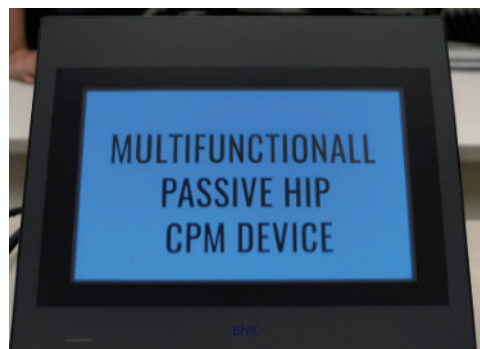


Fig. 11. (Color online) HMI for dual-axis control and parameter setting.

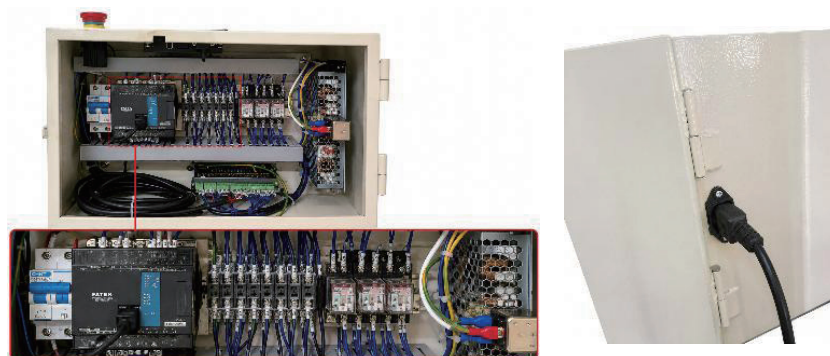


Fig. 12. (Color online) Electrical control cabinet integrating PLC, drivers, and relays.

In addition, the device satisfied the evaluated electrical safety and electromagnetic compatibility (EMC) requirements and completed mechanical load and support-strength testing, supporting the safety and structural reliability of the developed system.

3.1 System design and motion performance

The dual-axis CPM rehabilitation device was developed with a modular mechanical structure that emphasizes ergonomic safety, motion control, and ease of maintenance. The key innovation lies in its dual-axis configuration, which integrates independent modules for flexion and abduction to reproduce natural hip joint motion. This design expands the rehabilitation range beyond conventional single-axis CPM systems that only perform flexion–extension movement, allowing more comprehensive hip rehabilitation.

Each motion module was designed to operate smoothly within a defined angular range. The flexion module provides a hip flexion angle ranging from 0 to 90° and is driven by a stepper motor and lead-screw mechanism [Figs. 13(a) and 13(b)]. The abduction module enables lateral displacement up to 30°, actuated by a linear actuator and rotary linkage to simulate hip abductor movement [Figs. 14(a) and 14(b)]. The upper limit of hip flexion was set at 90° to remain within a commonly used postoperative precaution during early rehabilitation after total hip arthroplasty, in which excessive hip flexion beyond 90° has traditionally been restricted. The abduction range of 0–30° provides an adjustable lateral motion range for postoperative rehabilitation. These motion ranges are intended to provide a controllable rehabilitation motion envelope and can be adjusted according to individual rehabilitation requirements. Both modules share a lightweight aluminum frame and modular interface, allowing easy assembly, alignment, and maintenance.

To further clarify the design characteristics of the proposed system, its main functions were compared with representative commercial lower-limb CPM devices, as summarized in Table 1.

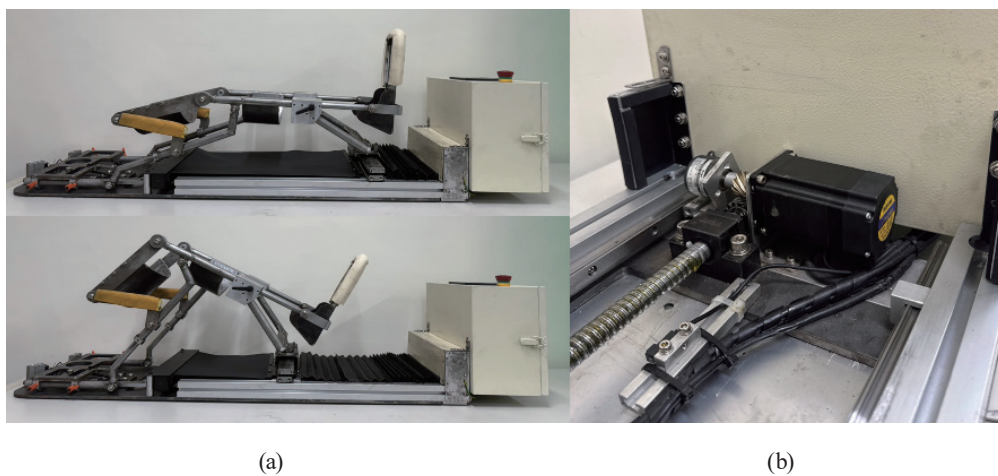


Fig. 13. (Color online) (a) Flexion motion test of CPM system over a hip flexion range of 0–90°. (b) Close-up view of the stepper motor and lead-screw mechanism.

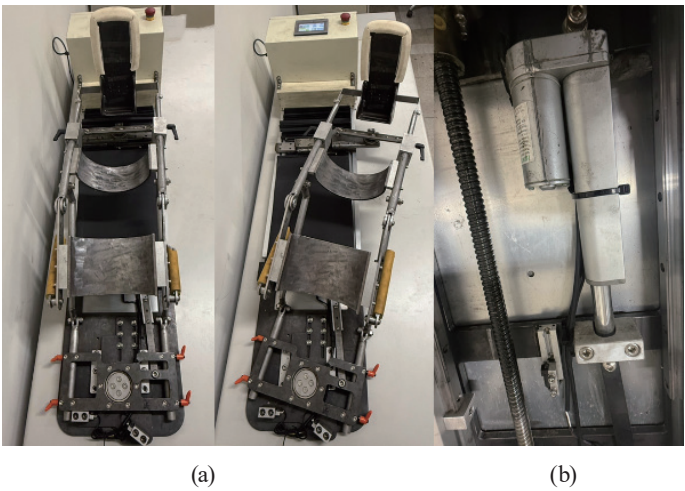


Fig. 14. (Color online) (a) Abduction motion test showing lateral movement over 0–30° range. (b) Close-up view of linear actuator and rotary linkage mechanism.

Table 1
Comparison of commercial and proposed CPM devices.

Device	Reported motion range	Motion type	Control method	Safety features
Proposed CPM device	Hip flexion: 0–90° Hip abduction: 0–30°	Independently actuated flexion and abduction	PLC-HMI control	Four endpoint sensors, overtravel protection, and emergency stop
Fisiotek 3000 series	Hip: –7–115°	Hip and knee flexion–extension	Programmable electronic control; remote START/STOP and programmable keypad	Remote START/STOP and programmable motion functions
Kinetec spectra	Flexion: –10–120°	Flexion–extension; foot positioning allows abduction/adduction adjustment	Digital remote control; adjustable ROM, speed, pauses, and programs	Patient lock-out, force-reversal function, START/STOP/Reverse

Compared with these representative commercial CPM systems, the proposed device integrates independently actuated hip flexion and abduction modules within a single rehabilitation platform. In addition, the PLC–HMI control architecture and endpoint sensing functions integrate programmable motion control, travel-limit detection, overtravel protection, and emergency-stop operation.

The mechanical layout ensures balanced torque distribution and structural rigidity while maintaining portability suitable for clinical and home-based applications. A compact PLC-based control unit was incorporated to coordinate both motion axes, supporting the coordinated and consistent operation of the mechanical system.

3.2 Manufacturing and assembly

All structural components of the dual-axis CPM rehabilitation device were manufactured through precision machining and cutting processes, including milling, turning, drilling, and laser cutting. These fabrication methods ensured consistent dimensional accuracy and mechanical reliability across all modules. The major components—such as side frames, linkage arms, brackets, and actuator housings—were machined from aluminum alloy and stainless steel to provide adequate rigidity and corrosion resistance.

During the assembly stage, each motion module was preassembled and aligned before integration into the main frame. The flexion module was connected to the base through a lead-screw support system, while the abduction module was mounted using a rotary linkage and actuator bracket to maintain proper alignment between motion axes. All structural joints were secured using alignment connectors to ensure smooth transmission and stable operation.

To enhance user safety and component protection, a dustproof sleeve was installed over the linear actuator, and a retractable cover was added around the lead-screw drive to prevent particle intrusion and accidental contact during operation (Fig. 15). The electrical control cabinet was firmly mounted at the front end of the CPM device, supported by a rigid aluminum bracket to enhance stability and accessibility while keeping the wiring organized and protected (Fig. 16).

3.3 Testing and certification evaluation

The functional verification of the dual-axis CPM rehabilitation device was performed to evaluate motion execution, operational stability, and control functionality. The testing process included both mechanical operation tests and control system evaluation to ensure compliance with clinical rehabilitation requirements. The certification-related evaluation focused on operational stability, safety mechanisms, and user interface reliability (Fig. 17).

Following these evaluations, the developed CPM device obtained Verification of Compliance certificates issued by the Precision Machinery Research & Development Center for IEC 60601-1:2005+A1:2012+A2:2020 and IEC 60601-1-2:2014+AMD1:2020. The clinical study protocol involving the developed CPM device also received Institutional Review Board (IRB)



Fig. 15. (Color online) Installation of dustproof sleeve and protective cover on dual-axis CPM rehabilitation device to prevent dust intrusion and ensure operational safety during motion.



Fig. 16. (Color online) Front-mounted control cabinet support bracket of dual-axis CPM rehabilitation device.



Fig. 17. (Color online) Functional testing setup of dual-axis CPM rehabilitation device, showing the control cabinet, HMI, and data monitoring through the connected laptop.

approval, allowing participant enrollment and clinical evaluation to proceed in accordance with the approved study protocol. The corresponding Verification of Compliance certificates and IRB approval document are shown in Fig. 18.

Mechanical load and support-strength tests were also performed to evaluate structural reliability. During the repeated-operation test, a leg load of up to 25 kg was applied to the leg-support region while the device repeatedly performed hip flexion (0–90°) and abduction (0–30°) motions. In addition, a static whole-device load of up to 150 kg was applied to evaluate structural integrity. After the load tests, no apparent structural deformation, loosening, fracture, or functional failure was observed, and the device remained capable of performing the programmed flexion and abduction motions.



Fig. 18. (Color online) Certification and ethical approval documents for the developed CPM device: (a) IEC 60601-1 Verification of Compliance certificate, (b) IEC 60601-1-2 Verification of Compliance certificate, and (c) IRB approval document.

The present prototype evaluation focused on the execution of the programmed hip flexion and abduction ranges, endpoint detection, safety functions, and repeated operation under mechanical loading conditions. Continuous angular tracking, torque measurement, and vibration-amplitude measurements were not included in the present evaluation. Therefore, the current results are interpreted as functional verification rather than a quantitative assessment of motion accuracy.

During operation, the CPM device demonstrated smooth and coordinated motion between the flexion and abduction modules under repeated cycles. The control interface, integrated with the PLC–HMI system, allowed therapists to adjust the abduction time and flexion–extension speed independently, providing greater flexibility for personalized rehabilitation programs.

All protection features—including the dustproof sleeve, retractable cover, and control cabinet housing—functioned effectively during extended operation without overheating or component wear. These results confirm that the developed system achieves stable performance, adjustable motion parameters, and reliable electrical control, providing a technical basis for subsequent clinical validation and regulatory evaluation.

3.4 Electrical control and HMI operation

The electrical control system of the developed dual-axis CPM rehabilitation device integrates the PLC and HMI to coordinate motion control and enhance usability. The PLC adopts a ladder logic program to execute the programmed motion sequence for both flexion and abduction

modules. Control commands are transmitted to the corresponding drive units, while endpoint sensor and emergency-stop signals are processed as safety inputs. This control architecture enables coordinated motion sequencing, endpoint position detection, and overtravel protection during rehabilitation training.

The HMI serves as the primary user interface, providing intuitive touchscreen control for parameter settings such as motion angle, operation time, and movement speed (Fig. 19). Users can easily switch between manual and continuous modes, adjust the abduction duration, and start or stop the device through dedicated control buttons. This configuration allows the rehabilitation parameters to be adjusted according to different training requirements. During system operation, the four endpoint sensors detected the predefined travel limits. Upon reaching an endpoint, the PLC stopped or reversed the corresponding actuator according to the programmed motion sequence. The emergency-stop function was also provided to immediately terminate actuator motion when required. Under simulated abnormal overtravel conditions, the control system stopped the corresponding actuator and displayed an alarm message on the HMI. These results confirmed the effectiveness of the endpoint sensing and safety feedback functions.

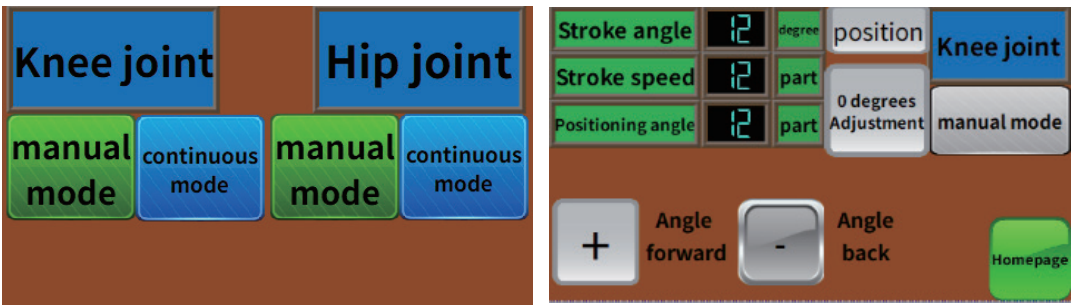


Fig. 19. (Color online) HMI control panel displaying adjustable parameters for flexion angle, speed, and abduction time.

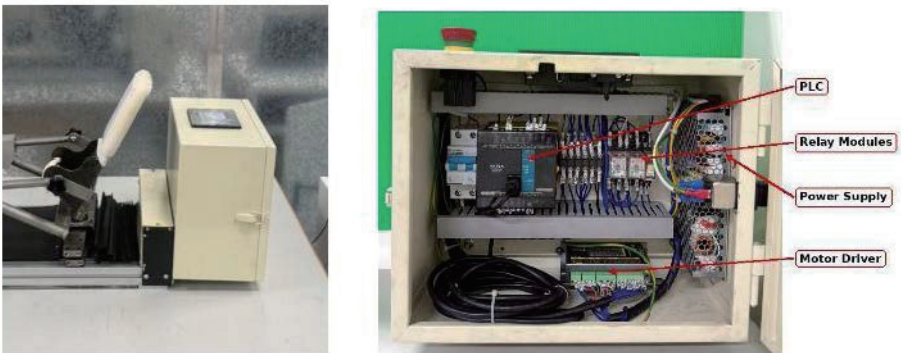


Fig. 20. (Color online) PLC control cabinet of dual-axis CPM rehabilitation device showing the integrated power, driver, and relay modules.

The PLC, motor drivers, relays, and power modules are housed inside the front-mounted control cabinet, while the HMI panel is installed at the top for convenient access during operation (Fig. 20).

4. Conclusions

The following conclusions were drawn from this study:

1. A dual-axis CPM rehabilitation device was successfully developed to assist postoperative hip rehabilitation, providing a hip flexion angle of 0–90° and an abduction angle of 0–30° for comprehensive joint training.
2. The flexion module, driven by a stepper motor and lead-screw mechanism, and the abduction module, actuated by a linear actuator and rotary linkage, demonstrated smooth and stable operation during repeated testing.
3. The PLC–HMI control system enabled the adjustment of the motion angle, speed, operating time, and operation mode. Four endpoint position sensors installed at the 0 and 90° limits of the flexion module and the 0 and 30° limits of the abduction module provided origin detection, travel-limit detection, overtravel protection, and HMI-based alarm notification.
4. The device obtained Verification of Compliance certificates for electrical safety and EMC in accordance with IEC 60601-1:2005+A1:2012+A2:2020 and IEC 60601-1-2:2014+AMD1:2020, respectively. Mechanical load testing under leg-support and whole-device loading conditions further confirmed the structural integrity of the system.
5. Compared with representative commercial lower-limb CPM systems, the proposed device expands hip rehabilitation motion by integrating independently actuated flexion and abduction modules with PLC–HMI control and endpoint safety sensing. This configuration provides greater motion versatility and adaptability for postoperative hip rehabilitation.
6. Future work will focus on clinical validation to further evaluate therapeutic efficacy and support subsequent regulatory evaluation. Quantitative assessment using external motion tracking may be conducted to determine angular accuracy and repeatability, while patient-specific motion profiles and force monitoring with threshold-based automatic termination may also be investigated to improve adaptability and safety for future clinical application.

Acknowledgments

This work was supported by the National Science and Technology Council (NSTC), Taiwan, under Grant No. NSTC 113-2221-E-224-068-MY3.

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