Wearable Physiotherapeutic Device For Stroke Affected Upper Limb Rehabilitation

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Abstract: This paper describes the design and development of a portable and wearable physiotherapeutic device for upper limb rehabilitation in stroke patients. Hemiplegia, a prevalent post-stroke motor disability, demands continuous and repetitive physiotherapy for successful rehabilitation. The existing rehabilitation process is time-consuming, costly, cumbersome, and demands frequent visits to hospitals, making it inaccessible and impractical for long-term use. The proposed device utilizes a modular control design with the aid of two separate Arduino-based microcontrollers to control the mechanical and pneumatic systems independently. Stepper motors facilitate accurate elbow flexion and extension as well as forearm pronation and supination movements, while a pneumatic system drives a soft silicone actuator for finger flexion and extension. Independent control of the subsystems enables safe, accurate, and repetitive therapeutic movements with improved reliability. The hybrid actuation strategy integrates rigid motor-driven motion with soft actuation for improved patient safety and comfort. The device provides a cost-effective and portable solution for home-based rehabilitation, enabling patients to undergo physiotherapy at home, thus reducing hospital dependence and enabling continuous rehabilitation and improved quality of life.

Index Terms - Stroke Rehabilitation, Stepper motor, Pneumatic actuator, Arduino control.

I. INTRODUCTION

Stroke is one of the top causes of long-term disability worldwide. It creates major medical, social, and economic challenges. Stroke happens when the blood supply to a part of the brain stops or when a blood vessel in the brain breaks. This leads to a lack of oxygen, lasting damage to nerve cells, and disruption of motor and sensory pathways. One common and serious result of stroke is hemiplegia. This condition causes partial or total paralysis on one side of the body and results in long-lasting motor problems. It greatly affects the ability to use the upper limbs, including shoulder stability, bending and straightening of the elbow, rotating the forearm, and fine finger movements necessary for coordinated tasks. Consequently, stroke survivors find it hard to carry out daily activities such as eating, dressing, writing, holding objects, and keeping clean, which often increases their reliance on caregivers. Long-term motor issues can also lead to further problems like muscle stiffness, spasticity, joint tightness, and decreased range of motion, which hinders recovery. In addition to physical challenges, these limitations impact mental health, leading to lower self-confidence, social isolation, and a drop in overall quality of life. Ongoing, repetitive, and task-focused physiotherapy is critical to restoring movement, building muscle strength, preventing additional issues, and encouraging neural reorganization through neuroplasticity, which is vital in recovering from a stroke. [2].

Despite its clinical importance, traditional stroke rehabilitation mainly relies on therapist-assisted manual training in hospitals or specialized rehab centers. While this method works, it requires frequent visits, long therapy sessions, and constant professional supervision. This makes rehabilitation costly, time-consuming, and physically challenging for both patients and caregivers. The situation worsens due to the limited number of trained physiotherapists and rehabilitation facilities, especially in rural and under-resourced areas, often leading to inadequate or interrupted therapy. To tackle these issues, recent progress in robotics, automation, and control

systems has led to the creation of robotic-assisted rehabilitation devices that can deliver precise, repetitive, and controlled therapeutic movements [1]. Wearable robotic systems and upper-limb exoskeletons have shown promising results in improving motor coordination, joint range of motion, and muscle activation. However, their high costs, mechanical complexity, and reliance on clinical settings limit their widespread use [3]. As a result, there is increasing demand for compact, affordable, and user-friendly rehabilitation solutions for home therapy. To meet this need, a wearable upper-limb rehabilitation system is proposed that uses a hybrid actuation strategy. This system combines motor-driven joint motion with compliant pneumatic soft actuation to ensure safe, effective, and accessible rehabilitation while supporting long-term recovery and improving quality of life.

II. METHODOLOGY

The hardware architecture of the proposed wearable upper-limb rehabilitation system is designed for modularity, reliability, and safe operation by separating the mechanical and pneumatic control subsystems. This design allows for precise control of joint movements while ensuring safe actuation for finger rehabilitation. The system includes multiple microcontrollers, power management units, motor drivers, and pneumatic components to coordinate the elbow, wrist, and finger motions needed for effective therapeutic exercises.
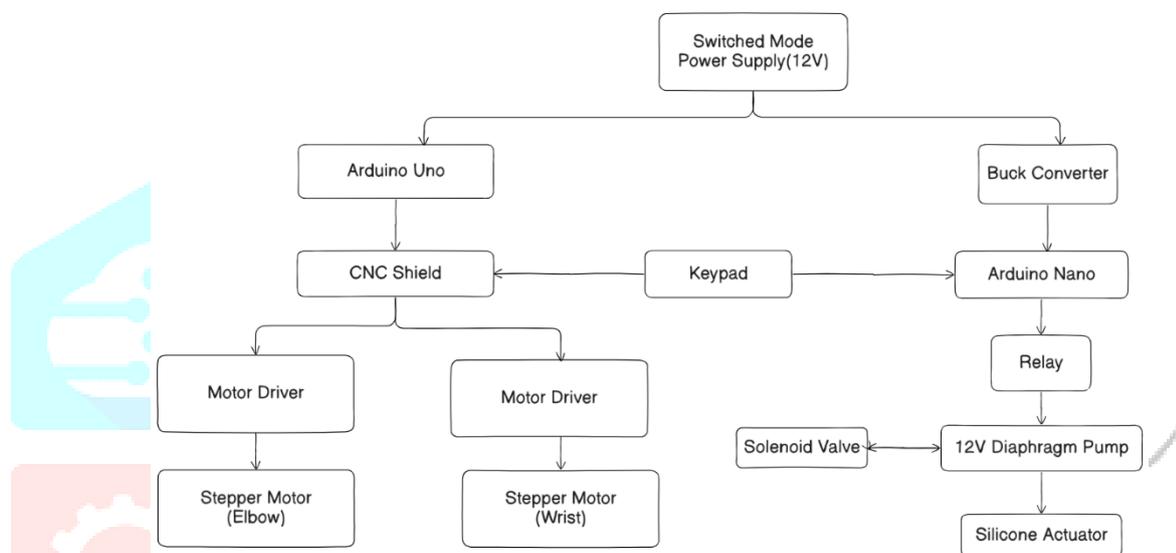

Figure 1. Block Diagram of Wearable Physiotherapeutic Device

The block diagram of the proposed wearable upper-limb rehabilitation system is shown in Fig. 1, illustrating the overall organization of the power supply, control units, actuation modules, and user interface. The system is powered by a centralized 12 V switched-mode power supply (SMPS), which provides the required electrical energy for both the mechanical and pneumatic subsystems. For mechanical joint actuation, an Arduino Uno is employed as the primary controller due to its reliability and compatibility with motor control hardware. The Arduino Uno interfaces with a CNC shield that simplifies the integration of stepper motor drivers and provides organized signal routing. Two motor driver modules mounted on the CNC shield independently control the stepper motors responsible for upper-limb joint movements. One stepper motor facilitates elbow flexion and extension, while the second controls wrist or forearm motion, enabling precise, repeatable, and controlled joint movements essential for physiotherapy. The motor drivers ensure accurate current regulation and smooth motion, thereby improving positional accuracy and reducing mechanical stress during repetitive rehabilitation exercises. A keypad interface is incorporated to allow user interaction, enabling selection of therapy modes, adjustment of motion parameters, and initiation of rehabilitation sequences.

The pneumatic actuation subsystem, depicted on the right side of Fig. 1, operates independently to enhance system modularity and safety. An Arduino Nano is used as a dedicated controller for pneumatic operations and is powered through a buck converter that steps down the 12 V supply to a regulated 5 V suitable for low-power electronics. This separation of control units minimizes electrical interference and ensures stable operation of both subsystems. The Arduino Nano controls a relay module that switches a 12 V diaphragm pump, which generates pressurized air required for soft actuation. Airflow from the pump is regulated using a solenoid valve that precisely controls the inflation and deflation of the silicone-based soft actuator. This arrangement enables compliant and safe finger flexion and extension movements, reducing the risk of injury and enhancing user comfort. The hybrid actuation architecture presented in Fig. 1 effectively combines rigid

motor-driven precision for elbow and wrist rehabilitation with pneumatic soft actuation for finger therapy. The modular design improves reliability, scalability, and suitability for home-based rehabilitation while ensuring coordinated and effective upper-limb physiotherapy.

III. HARDWARE DESIGN AND IMPLEMENTATION

3.1 3D DESIGN OVERVIEW

The mechanical and structural design of the proposed upper-limb rehabilitation system was developed using Autodesk Fusion 360, a computer-aided design (CAD) tool well suited for modeling complex biomedical devices. The software enabled precise visualization of the wearable framework, allowing the designers to align mechanical components with the natural anatomy of the human arm and hand. Emphasis was placed on ergonomic design to ensure user comfort during prolonged rehabilitation sessions, while maintaining sufficient structural strength to support motors, pneumatic actuators, and electronic modules. The design also considers modularity, enabling individual subsystems such as the elbow, forearm, and hand mechanisms to be assembled, adjusted, or replaced independently. This CAD-based approach helped in evaluating motion feasibility, component clearances, and overall system integration prior to fabrication, thereby reducing design errors and improving the reliability of the final prototype. Additionally, the virtual environment of Fusion 360 facilitated rapid design iterations, enabling modifications to be implemented efficiently based on functional requirements. The inclusion of realistic joint constraints allowed accurate simulation of elbow and wrist movements. Load distribution and mounting positions were also analyzed to minimize mechanical stress. Overall, the design process ensured a balance between functionality, safety, and user adaptability.
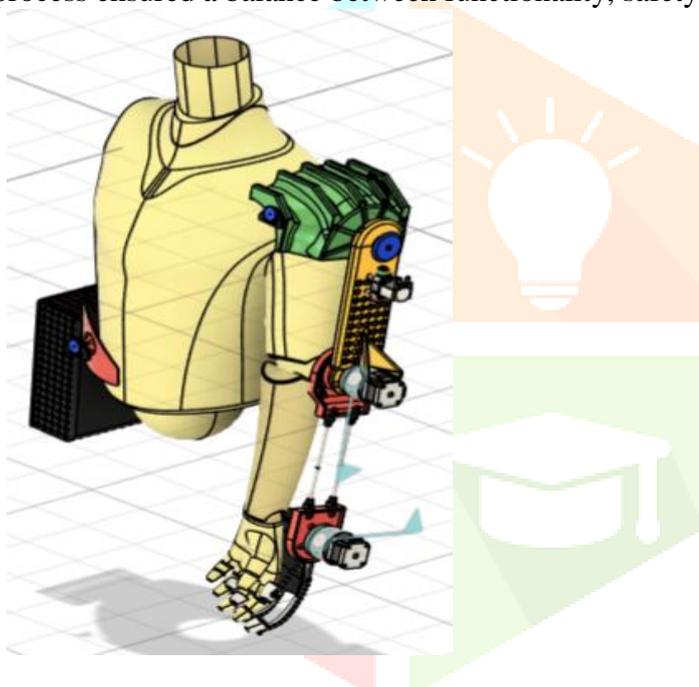

Fig. 2. 3D Design of wearable physiotherapeutic device for stroke affected upper limb

Fig. 3. 3D Design of finger actuator

The mechanical design of the proposed wearable upper-limb rehabilitation system is central to how the device works. Therefore, it was a top priority during development. The entire structure was modeled using Autodesk Fusion 360 to ensure precise control over dimensions, ergonomic fit, and effective integration of moving parts. As shown in Fig. 2, the complete CAD model includes interconnected modules for the elbow, forearm, wrist, and hand. These modules follow the natural movement pattern of the human upper limb. Each joint axis in the design was aligned with the anatomical joint to ensure that the assisted movements mimic natural motion and do not create unnatural forces on the user. Motor mounting brackets and structural links were strengthened to handle repeated loads during rehabilitation sessions while keeping a lightweight design to reduce user fatigue. Adjustable mounting points and strap interfaces were added to fit different arm lengths and sizes, making the device usable by patients with varying body types. The modular design allows sections to be removed or changed independently, making maintenance, future upgrades, and customization of therapy protocols easier. The hand rehabilitation module, shown in Fig. 3, was designed as a flexible structure to assist with finger flexion and extension. These movements are crucial for regaining hand function after a stroke. Soft silicone-based actuators were placed along the fingers to mimic tendon motion, allowing smooth bending and release without hard limits. The palm section acts as a stable base for these actuators while ensuring proper alignment with finger joints. This prevents discomfort or misalignment during repeated movements. The use of soft materials in the finger area improves safety by lowering the risk of applying too much force, making the system

suitable for patients with spasticity or limited control. Additionally, the compact and lightweight design of the hand module cuts down on inertia and boosts responsiveness during operation. By combining hard support elements with soft actuation, the design finds a good balance between stability and user comfort. Overall, the design shown in Fig. 2 supports natural movement, mechanical reliability, and effective therapy, making the system appropriate for continuous home-based rehabilitation of the upper limb.

3.2 HARDWARE PROTOTYPE

Figure 4. Hardware Prototype

The hardware prototype shown in Fig. 4 has two main parts that work together for effective upper-limb rehabilitation. The first part is a rigid electromechanical unit that provides controlled and precise movements of the elbow, forearm, and palm using stepper motors and mechanical linkages. This part ensures accurate joint motion, structural stability, and the repeatability needed for therapeutic exercises. The second part is a soft pneumatic unit designed for finger rehabilitation, which uses flexible silicone-based actuators powered by controlled airflow. Combining rigid motor-driven mechanisms with soft pneumatic actuation allows the system to provide safe, adjustable, and comfortable rehabilitation while addressing multiple movements of the upper limb.

A. Structural Fabrication and Motorized Actuation Subsystem

This subsystem includes the mechanical structure of the device and the electromechanical parts that control forearm and palm movement. Designers used computer-aided design (CAD) software to create a structural frame that closely resembles the human hand and forearm. This design also provides enough rigidity to support actuators, motors, and electronic modules. They chose Acrylonitrile Butadiene Styrene (ABS) thermoplastic as the fabrication material due to its high impact resistance, toughness, and compatibility with fused deposition modeling (FDM) 3D printing. When compared to biodegradable plastics like PLA, ABS holds up better against fatigue and thermal deformation. This makes it more suitable for devices that face repeated mechanical stress during rehabilitation exercises. The frame's geometry includes specific mounting points for motors, attachment points for support straps, and internal channels to route electrical wiring. This design ensures safe, compact, and smooth operation. The components were produced using an FDM-based additive manufacturing process. In this process, molten thermoplastic filament is deposited layer by layer to create the final structure. They optimized printing parameters such as layer thickness, infill density, and print orientation to find a good balance between mechanical strength and weight. Areas that experience higher stress, like motor mounts and joint regions, were printed with a higher infill density to improve structural integrity, while less critical sections used a lower infill to reduce the total weight. After fabrication, they removed support structures and finished the surface to eliminate sharp edges, improving user safety and comfort. The modular design of the frame lets users replace or modify individual components without having to rebuild the entire device.

Forearm rotation uses a NEMA 17 stepper motor mounted at the elbow joint of the frame. This motor was chosen for its high torque capability, precise position control, and compatibility with standard stepper motor drivers. It converts electrical pulses into precise angular movements. This allows for controlled and repeatable rotation needed for therapeutic forearm exercises. Mechanical coupling between the motor shaft and the forearm support structure uses rigid connectors. This setup ensures efficient torque transmission with minimal backlash. A suitable stepper driver module connects the motor to the control system. This connection allows for adjustments in stepping resolution, current limiting, and direction control. Palm flexion and extension come from a 12 V 28BYJ-48 geared stepper motor. This motor has an internal gear reduction mechanism that

significantly boosts output torque while slowing the rotational speed. This feature makes it ideal for low-force, high-precision hand rehabilitation tasks. A ULN2003 transistor array driver powers this motor. It boosts control signals from the microcontroller to the current levels needed by the motor windings. The coordinated operation of the NEMA 17 and 28BYJ-48 motors allows for combined forearm rotation and palm movement. This effectively imitates functional upper-limb motions. After installing, aligning, and testing all components, the assembled structure became a lightweight but sturdy platform. It can provide controlled mechanical support to users during their rehabilitation exercises.

B. Soft Actuation and Pneumatic Control Subsystem

The soft actuation subsystem generates finger motion using flexible pneumatic actuators made from silicone grade 00-50. This silicone grade was chosen for its high flexibility, low stiffness, biocompatibility, and ability to stretch significantly without permanent damage. Unlike rigid mechanical linkages, soft actuators spread contact forces over a larger surface area. This greatly lowers the chance of joint overstress and discomfort during therapy. The actuators were made using a molding process. Custom molds were created to match the desired finger shape. Liquid silicone was mixed and degassed to remove trapped air. Then, it was poured into mold cavities that contained internal cores to create air chambers. After the silicone cured, the actuators were taken out, sealed to form airtight structures, and connected to pneumatic tubing for pressurization. Finger bending occurs through the uneven expansion of the internal chambers when compressed air is introduced. A thicker base layer limits expansion on one side, causing the actuator to bend toward that direction during inflation. The curvature that results depends on the chamber shape, wall thickness, and air pressure applied. This design helps the motion closely mimic natural finger flexion while keeping its flexibility. When the pressure is released, the rubbery nature of the silicone lets the actuator return to its original shape without needing any mechanical components.

Pressurized air for the actuator operation comes from three miniature diaphragm pumps. Each pump serves a separate actuation channel, enabling independent finger control and preventing pressure drops during simultaneous use. Using multiple pumps improves system responsiveness and allows for customized rehabilitation patterns tailored to individual patient needs. Each pump gets power from a 5 V single-channel relay module. This module separates the high-current pump circuitry from the low-power control electronics, improving operational safety and protecting the microcontroller from electrical stress. An Arduino Nano microcontroller controls the relays. It runs predefined therapy sequences by managing pump activation, actuation duration, and rest periods. The system includes an NE555 timer circuit for stable triggering and precise timing control. This setup ensures consistent inflation and deflation cycles and prevents rapid switching that could shorten pump life or compromise system reliability. Airflow regulation happens through electrically actuated solenoid valves integrated into each pneumatic line. This design allows for accurate adjustment of actuator pressurization and release. When energized, the solenoid valve opens, letting pressurized air from the pump reach the soft actuator, which creates controlled finger flexion. When de-energized, the actuator passively deflates, thanks to the elastic restoring force of the silicone material. Flexible, airtight pneumatic tubing connects the pumps, valves, and actuators, forming a compact and organized pneumatic network. This arrangement minimizes leakage, pressure loss, and response delays. The modular design of the pneumatic components makes maintenance easier. It allows for the replacement of individual pumps or valves without impacting the whole system. Combining electronically controlled pneumatic components with compliant soft actuators results in a lightweight, adaptable, and safe rehabilitation mechanism. If there is a power interruption or system failure, the actuators will naturally depressurize and return to a relaxed state. This feature eliminates the risk of rigid locking and ensures patient safety during long therapy sessions.

IV. CONCLUSION

The wearable physiotherapy device offers a practical, reliable, and budget-friendly way to help people with upper-limb rehabilitation after a stroke. Its main goal is to assist patients in doing controlled and repetitive exercises to improve their joint mobility, muscle strength, and motor coordination. By combining motor-driven actuation for elbow flexion and extension with a soft pneumatic system for finger movements, the device creates smooth and safe motions similar to traditional physiotherapy exercises. The finished hardware prototype shows that it is possible to integrate electrical, mechanical, and pneumatic systems into a compact, wearable rehabilitation platform. The device uses stepper motors mounted on a 3D-printed ABS frame, which allows for precise, stable, and repeatable joint movements. A silicone-based soft actuator makes finger rehabilitation comfortable and safe for users. The Arduino-based control system coordinates all actuators and pneumatic parts to keep multiple joints working together. Great attention was given to ergonomic design, structural strength, and safety, making the device suitable for assisted therapy and supervised rehab settings.

Due to budget constraints and limited parts availability, the current version uses a simple open-loop control strategy without advanced sensors or real-time feedback. However, the modular design allows for future upgrades, including the addition of motion and force sensors, closed-loop control methods, and monitoring of patient progress. Overall, this system meets its aims by providing a functional, affordable, and flexible wearable physiotherapy option while laying a solid groundwork for future improvements to boost rehabilitation success and recovery results.

V. REFERENCES

[1] M. Dragusanu, M. Z. Iqbal, T. L. Baldi, D. Prattichizzo, and M. Malvezzi, "Design, development, and control of a hand/wrist exoskeleton for rehabilitation and training," IEEE Transactions on Robotics, vol. 38,no. 3, pp. 1472–1487, 2022.

[2] S. Rahman, S. Sarker, A. K. M. N. Haque, M. M. Utsha, M. F. Islam, and S. Deb, "AI-driven stroke rehabilitation systems and assessment: A systematic review," IEEE Transactions on Neural Systems and Rehabilitation Engineering, vol. 31, pp. 192–207, 2023.

[3] E. Ambrosini, J. Zajc, S. Ferrante, G. Ferrigno, S. D. Gasperina, M. Bulgheroni, W. Baccellini, T. Schauer, C. Wiesener, M. Russold, M. Gfoehler, M. Puchinger, M. Weber, S. Becker, K. Krakow, N. Immick, A. Augsten, M. Rossini, D. Proserpio, G. Gasperini, and A. Pedrocchi, "A hybrid robotic system for arm training of stroke survivors: Concept and first evaluation," IEEE Transactions on Biomedical Engineering, vol. 66, no. 12, pp. 3290–3296, 2019.

[4] W. Zhou, X. Li, J. Qian, M. Xia, Y. Pu, P. Jiang, and J. Huang, "Frequency modulation based on hyperbolic tangent function for position closed-loop control of stepper motor," IEEE Access, vol. 11, pp. 65066–65076, 2023.

[5] A. Pilla, E. Trigili, Z. McKinney, C. Fanciullacci, C. Malosoma, F. Posteraro, S. Crea, and N. Vitiello, "Robotic rehabilitation and multi-modal instrumented assessment of post-stroke elbow motor functions—Arandomized controlled trial protocol," Frontiers in Neurology, vol. 11, p. 587293, 2020.

[6] D.-W. Kim, J. E. Park, M.-J. Kim, S. H. Byun, C. I. Jung, H. M. Jeong, S. R. Woo, K. H. Lee, M. H. Lee, J.-W. Jung, D. Lee, B.-J. Ryu, S. N. Yang, and S. J. Baek, "Automatic assessment of upper extremity function and mobile application for self-administered stroke rehabilitation," IEEE Transactions on Neural Systems and Rehabilitation Engineering, vol.32, pp. 652–662, 2024.

[7] S. Li, Z. Wang, X. Yin, Z. Pang, and X. Yan, "Rehabilitation evaluation of upper limb motor function for stroke patients based on belief rule base," IEEE Transactions on Neural Systems and Rehabilitation Engineering, vol. 32, pp. 241–251, 2024.