TECHNICAL UNIVERSITY OF CLUJ-NAPOCA

ACTA TECHNICA NAPOCENSIS

Series: Applied Mathematics, Mechanics, and Engineering
Vol.68, Issue II, June, 2025

ROBOTIC SYSTEM FOR BILATERAL UPPER LIMB REHABILITATION

David - Daniel ROMAN, Silviu Dan MÂNDRU

Abstract: *This paper proposes an original robotic system for bilateral upper limb rehabilitation, targeting patients who have experienced partial or total loss of motor functions. The system employs advanced technologies and appropriate software, providing personalized exercises with real-time adjustment capabilities based on the patient's progress. The paper includes a comparative analysis of existing equipment, highlighting their advantages and limitations. The proposed solution integrates innovations such as precise motion tracking and a design that supports both symmetrical and asymmetrical movements, making it suitable for both clinical and home-based therapies. The system aims to enhance rehabilitation efficiency, emphasizing device adaptability and accessibility. The conclusions underline the benefits of using such equipment in medical rehabilitation and suggest future directions for expanding its functionalities.*

Key words: Robotic rehabilitation, exerciser, upper limb, bilateral therapy.

1. INTRODUCTION

Upper limb rehabilitation plays a critical role in restoring independence and quality of life for patients affected by trauma, neurological disorders, or orthopaedic conditions. The upper limbs are essential in daily functions, such as dressing, eating, and personal hygiene, which collectively contribute to a person's autonomy and self-esteem [1].

Recent advancements in robotic technology have introduced innovative solutions to physical therapy [2], enhancing both precision and customization in therapeutic exercises. According to [3]-[6], the bilateral exercises might be more effective for improving upper limb motor recovery in stroke patients compared to unilateral exercises. Bilateral exercises can also contribute to the reorganization of the cortical network, thus contributing to motor recovery. Traditional bilateral exercises involve activities such as: pushing and pulling with both arms (opening/closing two adjacent drawers), grasping and placing different objects using both hands, bilateral arm extension, etc. But, as with unilateral exercises, it has been proven that robotically assisted exercises are more effective. Thus, this paper explores a robotic system specifically designed for bilateral upper limb rehabilitation, providing adaptable and personalized exercises customized to each patient's therapeutic progress. The primary objective of this study is to overcome the challenges of traditional rehabilitation techniques, delivering an approach that enhances patient engagement and accelerates recovery.

2. COMPARATIVE ANALYSIS

In the field of bilateral upper limb rehabilitation, numerous robotic systems have been developed [3], each designed to address specific therapeutic needs and limitations. This analysis highlights key devices, emphasizing their functionality, adaptability, and potential impact on patient recovery.

Tailwind (BATRAC) device focuses on bilateral training, particularly for post-stroke recovery, [4]. Designed for home use, it supports a range of upper limb movements. Tailwind enhances shoulder and elbow extension, making it an accessible tool for improving recovery outcomes by enabling patients to engage in therapeutic exercises in a non-clinical environment. The same paper presents MIME,

Received: 30.04.25; **Similarities**: 29.05.25: **Reviewed**: 03.06./03.06.25: **Accepted**:19.06.25.

which is a 6-degree-of-freedom robot that allows movements in multiple physiological planes and facilitates bilateral upper limb training in post-stroke rehabilitation. It focuses on recovering motor functions at the shoulder and elbow levels by performing assisted movements. MIME is equipped with a 6-axis accelerometer and gyroscope sensor that measures forces and torque between the affected upper limb and the robot [4].

Bi-Manu-Track system facilitates pronation-supination and flexion-extension movements for the forearm and wrist, [5]. Its three modes passive-passive, active-passive, and active-active allow for customized rehabilitation based on the patient's motor capabilities. The ability to adjust amplitude, speed, and resistance ensures compatibility with various recovery stages. *Braccio di Ferro, o*riginally designed for unilateral rehabilitation, this system has been adapted for bilateral use. Its adjustable bar enables simultaneous arm movements, promoting muscle activation and joint flexibility [6].

BFIAMT (Bilateral Force-Induced Isokinetic Arm Movement Training) is a robotic system that assists patients in bilateral upper limb recovery in post-stroke rehabilitation, [7]. Training using BFIAMT focuses on improving the motor function of the affected upper limb, but also on improving grip strength, pushing and pulling strength. It is composed of two servomotors, two guides that allow patients to perform translational movements along them over a distance varying between 350 mm and 450 mm, two handles, forearm supports and a control panel. The device supports four different treatment modes: passive, active-passive, active and bilateral symmetrical movement of the upper limbs.

The analysis of various robotic solutions for bilateral upper limb rehabilitation highlights the diversity and innovation in the field of rehabilitation technologies. Each device has distinct features, addressing different patient needs. Many, although showing potential in limbs rehabilitation, are characterized by high complexity, high cost, and further research is needed to confirm their effectiveness.

3. PROPOSED VARIANTS

Our approach involved the proposal of three different variants/options, so that, based on a critical analysis, the variant that better meets the specific requirements of bilateral rehabilitation at the level of the upper limbs should be chosen.

The first variant (Figure 1) features a compact mechanism where handles are mounted inside subassemblies, moving along guides via belt transmission. The system employs motors for passive mobilization, allowing both symmetrical and asymmetrical movements. Its portability and adjustable handle distance enhance usability, but it lacks an inclination mechanism, limiting configuration flexibility.

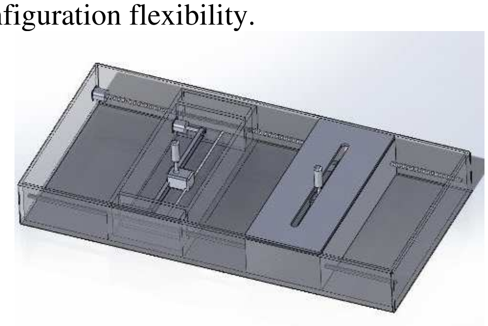

Fig. 1. The first variant of the robotic system for bilateral upper limb rehabilitation.

The second option (Figure 2) utilizes a single motor with a speed reducer to move handles in a circular trajectory, enabling asymmetrical passive mobilizations.

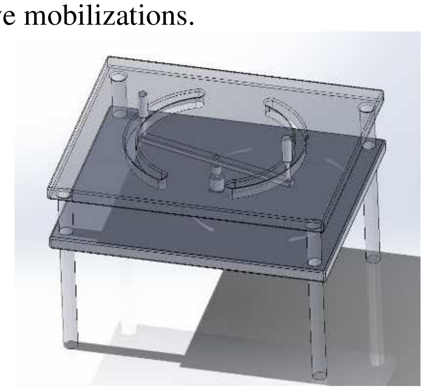

Fig. 2. The second variant of the robotic system for bilateral upper limb rehabilitation.

Its simplicity and lower development cost are key advantages. However, the single degree of freedom restricts movement diversity, and the lack of symmetrical motion may reduce its effectiveness for rehabilitation exercises.

The complex design of the third variant (Figure 3) includes an inclination mechanism, allowing a wide range of symmetrical and asymmetrical movements. It offers superior adaptability with adjustable handle distances and movement amplitudes. While its complexity and higher cost are potential drawbacks, the extensive functionality ensures a more personalized rehabilitation experience

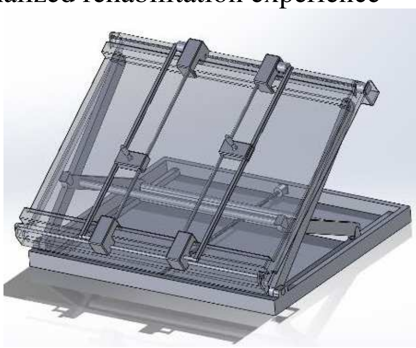

Fig. 3. The third variant of the robotic system for bilateral upper limb rehabilitation.

The main advantages and disadvantages of the proposed variants are emphasized in Table 1. In accordance with Table 1, the third variant is the preferred choice due to its ability to address a wide range of rehabilitation needs. Its inclination mechanism and capacity for both symmetrical and asymmetrical movements provide superior adaptability for individual users. Although it requires more maintenance and involves higher costs, the potential for enhanced recovery outcomes and personalized therapy justifies the selection of this solution.

Table 1 The advantages and disadvantages of the proposed variants

Variant	Advantages	Disadvantages
1	Allows stimulation for active motion by stopping the motors.	Lacks an inclination mechanism, limiting configuration flexibility.
	Compact design makes it portable.	Cannot be fully configured for individual user needs, potentially reducing rehabilitation efficiency.
2	Simplifies mechanism with a single motor, reducing production and maintenance costs.	Limited to one degree of freedom, restricting movement diversity.
	Curvilinear trajectory offers beneficial movement variety.	Asymmetrical motion may not always be the most effective for rehabilitation.
3	Inclination mechanism provides a wide range of movements customized to user needs.	Increased complexity raises the risk of malfunction and requires regular maintenance.
	Supports both symmetrical and asymmetrical simultaneous movements.	High cost due to the large number of components and functional complexity.

4. DESIGN AND DEVELOPMENT OF A DEMONSTRATOR

According to Figure 4a the user holds the two handles (4), performing movements along the guides (3). The device is equipped with motors (M2, M3) and belts (5) that set the handles in motion. The distance between the handles can be adjusted, the guides (3) perform a horizontal translational with the help of the motor (M1) and screw (1).

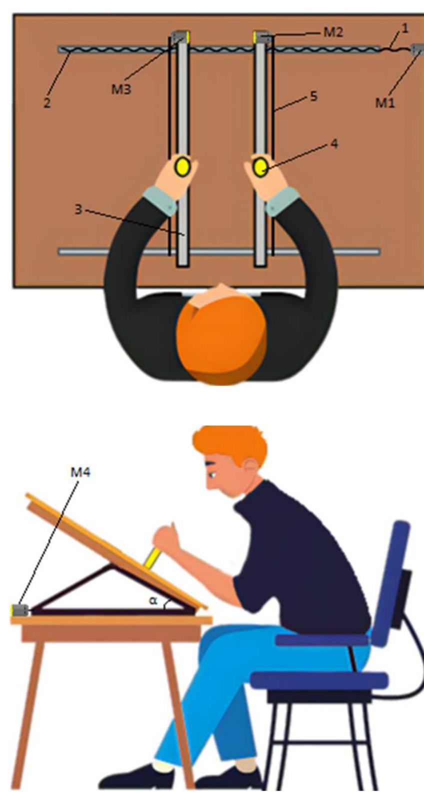

Fig. 4. The operation mode of the studied system.

Figure 4b shows the tilt mechanism that offers the possibility to adjust the angle α, being driven by the actuator (M4).

The workspace of the system must accommodate the anatomical and physiological movements required for effective therapy, ensuring compatibility with a wide range of patient profiles and therapeutic needs. Anthropometric studies reveal significant differences in upper limb lengths between genders. For women, the arm length varies between 600 and 740 mm, while for men, it ranges from 630 to 760 mm [8]. These values provide essential insights into the anatomical variability that must be accommodated in the system's design. Shoulder width is another crucial parameter influencing the device's design. Data indicate that the average shoulder width ranges from 340 to 480 mm for women and 400 to 530 mm for men [9]. These differences emphasize the need for adjustable components in the system to accommodate various anatomical configurations. Based on the anthropometric data, the following specifications have been defined for the robotic system: *Maximum Reach*: the system provides a maximum travel distance of 300 mm; *Adjustable Handle Distance*: the handle positioning is adjustable within a range of 150 mm to 500 mm to accommodate users of varying sizes and therapeutic requirements.

The handle positioning subsystem (Figure 5) enables smooth and precise handle positioning to accommodate different patient needs. It incorporates a motor-driven mechanism for translating handles along a linear guide. The following notations were used: 1-motor, 2, 2'-pulleys, 3-belt, 4-support (it acts as the connection element to the belt and holds the handle), 5-linear guide (ensures stable and accurate movement of the handle assembly along the x-axis; its maximum travel distance is C = 300 mm, allowing sufficient range for various rehabilitation exercises), 6-handle (which is directly attached to the support and serves as the interaction element with the patient, moving along the linear guide).

For travel durations $t_{min} = 5\ s$ and $t_{max} = 20\ s$, the corresponding linear speeds v_4 and the angular speeds of the motor ω_1 were calculated, as well as the motor's frequency f considering the step angle $\varphi_p = 1.8°$. Considering the frequency and the total resistive torque at the motor shaft M_r^r, the stepper motor has been verified in terms of the torque developed at the working frequencies.

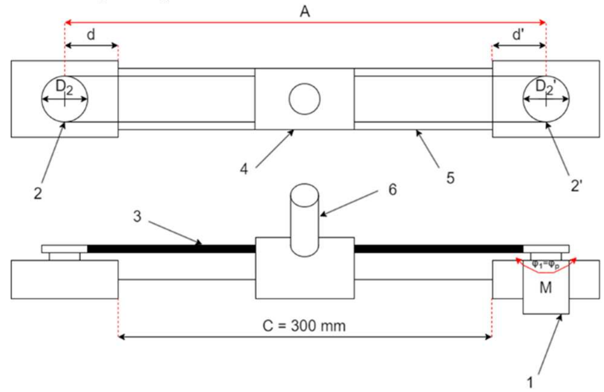

Fig. 5. Schematic representation of the handle positioning subassembly.

The handle distance adjustment subassembly allows the user to adjust the position of the handles according to the exercise requirements, which contributes to proper alignment and balanced training.

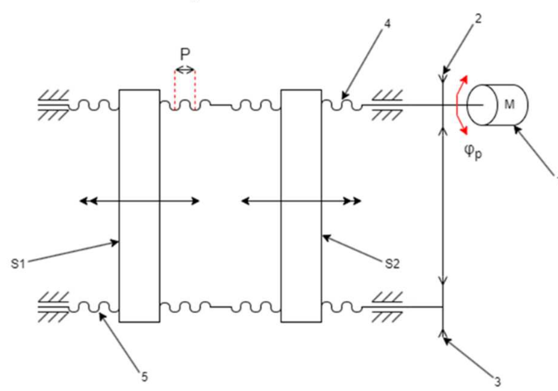

Fig. 6. Schematic representation of the handle distance adjustment subassembly.

According to Figure 6, the motor (1) drives the system and is connected to screw (4) through a flexible coupling; the pulley (2), the belt and pulley (3) transmit the motor's motion to screw (5), for a synchronized rotation of both screws. Screw (4) and screw (5) feature left-handed threads on one half and right-handed threads on the other. This dual-threaded design allows the handle support subassemblies, S1 and S2, to move symmetrically closer together or further apart as the screws rotate, enabling precise distance adjustments between the handles.

The device inclination subassembly (Figure 7) enables users to adjust the device's angle according to their individual needs and therapeutic goals. This adjustment enhances the device's versatility, ensuring that it can accommodate various rehabilitation exercises and user profiles.

Proper inclination adjustment supports optimal positioning during therapy sessions, improving user comfort and maximizing the device's efficiency in delivering effective rehabilitation outcomes.

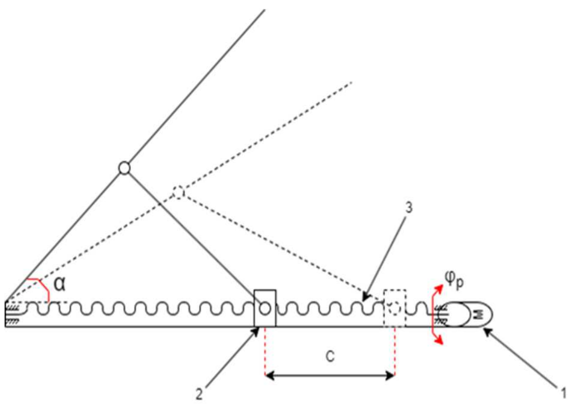

Fig. 7. Schematic representation of the device inclination subassembly.

The stepper motor (1) is connected to the lead screw (3) through a flexible coupling. The slider (2) incorporates a nut that engages with the threading of the lead screw; as the motor rotates the screw, the slider assembly translate linearly. This linear movement of the slider adjusts the tilt angle α of the device.

The system can achieve inclinations ranging from 0 to 45 degrees, providing sufficient flexibility for rehabilitation exercises that require specific angular positioning. The maximum travel distance of the slider (C), determines the full range of inclination achievable by the system.

Figure 8 shows the 3D model of the studied system. Each subassembly of the three presented above has been designed to ensure the efficiency and reliability of the device in the bilateral rehabilitation process. Figure 9 present the electrical diagram, described in detail in [10], designed to control the four stepper motors.

The core components consist of an *Arduino UNO* development board, *CNC Shield V3*, four

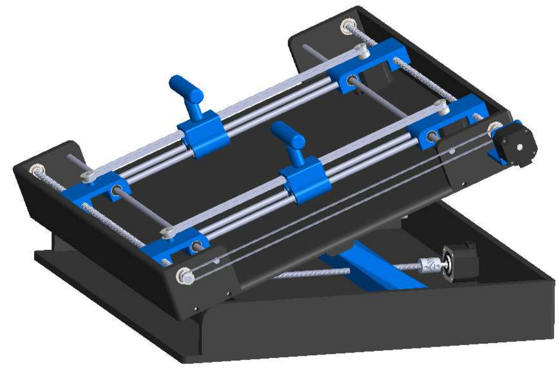

Fig. 8. The 3D model of the device.

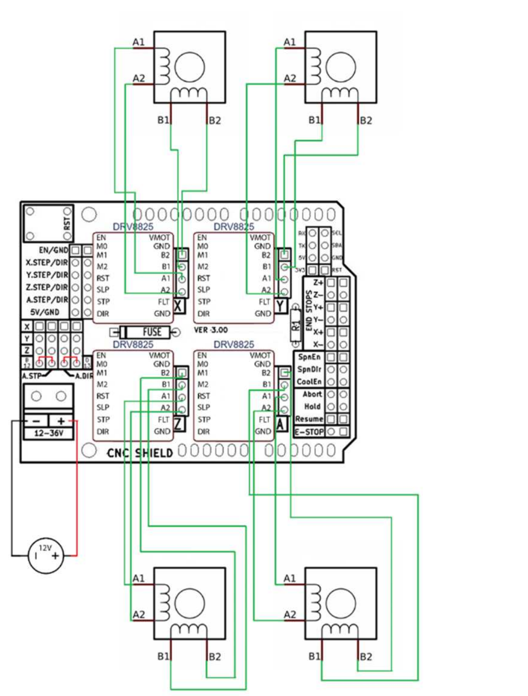

Fig. 9. The electrical diagram of the bilateral upper limb rehabilitation system.

DRV8825 stepper motor drivers, and four *Nema 17* stepper motors, all powered by a dedicated 12V DC power supply. The CNC Shield V3 is directly mounted onto the Arduino UNO and serves as the primary interface for controlling the four stepper motors. Each DRV8825 driver is carefully mounted on designated slots labeled X, Y, Z, and A on the CNC Shield, controlling their respective motors via connections to terminals A1, A2, B1, and B2. Two jumpers placed on pins D12 and D13 activate the step and direction functionalities for the "A" axis.

The DRV8825 drivers provide up to 1/32 micro-stepping capability, essential for achieving fine and precise motor movements required for effective therapeutic exercises. These drivers support a maximum current of up to 2.2A per phase without additional cooling mechanisms, offering reliability during prolonged usage. The Arduino UNO, powered by the ATmega328P microcontroller, provides robust control capabilities through 14 digital input/output pins, 6 analog inputs, a 16 MHz oscillator, USB connectivity, and dedicated power inputs, ensuring flexibility and ease of programming.

To ensure electrical safety and prevent overheating, a cooling strategy based on passive aluminum heatsinks was implemented for each driver. Additionally, polyfuse resettable fuses were added to protect against overcurrent scenarios, particularly during intensive movement cycles or continuous operation. Signal integrity and electromagnetic compatibility were also considered by incorporating decoupling capacitors near each driver and separating power and signal wiring paths where possible.

Moreover, the modularity of the control architecture allows easy integration of additional features, such as end-stop sensors, emergency stop buttons, or wireless communication modules (e.g., Bluetooth or Wi-Fi), which can be connected through available digital I/O pins. This flexible setup enables future expansion and customization depending on therapeutic protocol requirements or clinical feedback.

5. RESULTS

Based on the above presented design approaches, a demonstrator of the bilateral rehabilitation robotic system was developed (Figure 10). Low-cost materials and manufacturing processes were used, along with commercially available components to realize both the mechanical and electronic modules.

Special attention was given to the ergonomic integration of the system, ensuring that interaction points such as handles and interface elements are comfortable and intuitive for users with varying physical limitations. The structural elements were designed to provide stability during operation while allowing easy access for therapists or patients when adjustments or supervision are needed. The entire system can be set up quickly, requiring minimal training, which is critical in clinical environments where time efficiency and user-friendliness are essential.

Another major consideration in developing the demonstrator was the scalability and potential for future upgrades. The modular architecture allows components such as motors, sensors, or control boards to be replaced or expanded with minimal redesign. This makes the system suitable not only for research and prototyping purposes but also for potential clinical trials or customization for specific patient groups. The design supports future implementation of additional sensors or wireless communication to further enhance therapy personalization.

Fig. 10. The developed demonstrator.

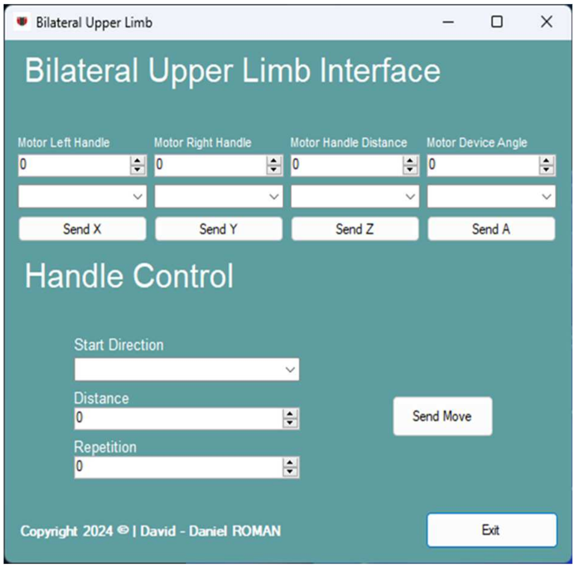

Fig. 11. The proposed user interface.

The C++ language was used to program the Arduino board, using the Arduino IDE integrated development environment. The developed Arduino code defines and initializes pins corresponding to motor drivers for four axes (X, Y, Z, and A). In the setup function, each pin is configured as an output, and the serial communication is initialized to facilitate command reception from the graphical user interface (GUI). The loop continuously listens for incoming serial commands, parsing them to determine the specific motor, direction, and number of steps required. This approach allows precise motor control based on user-defined commands, ensuring movements are accurately executed according to therapy needs.

The graphical user interface was programmed in C# using Visual Studio software, specifically Windows Forms and .NET Framework 4.7.2, ensuring easy and intuitive interaction for users. The interface (Figure 11) includes 6 *buttons*, 6 *NumericUpDown* controls, and 5 *ComboBox* controls. NumericUpDown controls allow users to set distances each motor must travel, adjust distances between handles, and specify device tilt angles. ComboBox controls determine motor directions (front/rear). Interaction buttons labeled "*Send X*", "*Send Y*", "*Send Z*", and "*Send A*" send defined parameters to respective motors. The "*Send Move*" button enables execution of predefined repetitive rehabilitation exercises.

Behind each GUI button lies corresponding event-driven logic that constructs specific commands in a structured format (motor, direction, steps), which are transmitted via serial communication to the Arduino. These commands trigger the Arduino's motor-control logic, resulting in precise movements. Users can customize exercises by defining direction, distance, and repetition count, facilitating personalized therapeutic routines.

The developed equipment was tested by three healthy subjects to verify that it functioned as designed. Following these preliminary tests, the equipment worked well. For future experimental tests conducted by various medical staff, a questionnaire was proposed, to find out satisfaction with using the proposed system as well as the performance of the system.

6. CONCLUSION

This study has introduced a robotic system for bilateral upper limb rehabilitation, designed to address the diverse needs of patients recovering from motor function impairments. The system incorporates advanced technologies and anthropometric considerations to deliver personalized and ergonomic therapy. Key features such as adjustable handle distances and customizable motion amplitudes ensure compatibility with a wide range of anatomical and therapeutic requirements, enabling effective rehabilitation across various patient profiles.

By addressing the limitations of traditional methods, the proposed system enhances recovery efficiency through real-time adaptability, precise motion tracking, and a focus on user engagement.

The research conducted opens new perspectives, thus the future research will aim to improve the system’s functionality (implementing preset exercises and rehabilitation programs that cover a wider range of diseases and difficulty levels; implementing auditory feedback to assist and stimulate the user in the process of bilateral upper limb recovery; development of a mobile application connected to the equipment to allow the user to monitor own progress and receive personalized instructions in real time, integrating a remote monitoring system so therapists can oversee user's progress, development of customized functions for patients with various disabilities, for example, voice commands for patients with reduced hand mobility) as well as to validate its clinical effectiveness, paving the way for broader applications in rehabilitation therapies and improved patient outcomes.

7. REFERENCES

[1] Bogdan, R., Bucur, A., Chiriac, M., Ciobanu D., *Kinetoterapie/Physiotherapy*, Editura Universității din Oradea, 2006

[2] Banyai, A., Brișan, C., *Robotics in Physical Rehabilitation: Systematic Review*, Healthcare, Volume 12, DOI: 10.3390/healthcare12171720, 2024

[3] Tang, C., Zhou, T., Zhang, Y., Yuan, R., *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, Volume 28, DOI: 10.1186/s40001-023-01565-x, 2023

[4] Delden, A., Peper, C., Kwakkel, G., Beek, P., *A Systematic Review of Bilateral Upper Limb Training Devices for Poststroke Rehabilitation*, Stroke Research and Treatment, Volume 2012, DOI: 10.1155/2012/972069, 2012

[5] Hesse, S., Tigges, G., Konard, M., Bardeleben, A., *Robot-Assisted Arm Trainer for the Passive an Active Practice of Bilateral Forearm and Wrist Movements in Hemiparetic Subjects*, Archives of Physical Medicine and Rehabilitation, Volume 84, DOI: https://doi.org/10.1016/S0003-9993(02)04954-7, 2003

[6] Casadio, M., Sanguineti, V., Morasso, P., Arrichiello V., *Braccio di Ferro: A new haptic workstation for neuromotor rehabilitation*, Technology and Health Care, Volume 14, 2006

[7] Chang, J., ș. a., *Effects of Robot-Aided Bilateral Force-Induced Isokinetic Arm Training Combined With Conventional Rehabilitation on Arm Motor Function in Patients With Chronic Stroke*, Archives of Physical Medicine and Rehabilitation, Vol. 88, DOI: 10.1016/j.apmr.2007.07.016, 2007

[8] *Statistics About The Average Arm Size*, https://gitnux.org/average-arm-size/

[9] *Statistics About The Average Shoulder Width*, https://gitnux.org/average-shoulder-width/

[10] Roman, D., *Proiectarea unui echipament pentru recuperarea bilaterală a membrelor superioare*, Proiect de diplomă, Universitatea Tehnică din Cluj-Napoca, 2024

Proiectarea unui echipament pentru recuperarea bilaterală a membrelor superioare

Rezumat: *Articolul propune proiectarea unui sistem robotic destinat reabilitării bilaterale a membrelor superioare, adresându-se pacienţilor care au suferit pierderi parţiale sau totale ale funcţiilor motorii. Sistemul utilizează tehnologii avansate şi un software adaptiv, oferind exerciţii personalizate şi posibilitatea de ajustare în timp real, în funcţie de progresul pacientului. Lucrarea include o analiză comparativă a echipamentelor existente, evidenţiind avantajele şi limitările acestora. Soluţia propusă integrează inovaţii precum urmărirea precisă a mişcărilor şi un design care facilitează atât mişcări simetrice, cât şi asimetrice, fiind aplicabilă în terapii clinice şi la domiciliu. Sistemul urmăreşte să îmbunătăţească eficienţa recuperării, punând accent pe adaptabilitatea şi accesibilitatea dispozitivului. Concluziile subliniază beneficiile utilizării unui astfel de echipament în recuperarea medicală şi propun direcţii viitoare pentru extinderea funcţionalităţilor.*

David - Daniel ROMAN, Eng., Master of Science Student, Technical University of Cluj-Napoca, Computer Science, david.roman2001@yahoo.com, ROMANIA

Silviu Dan MÂNDRU, Prof. Dr. Eng., Technical University of Cluj-Napoca, Department of Mechatronics and Machine Dynamics, dan.mandru@mdm.utcluj.ro, ROMANIA