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PATIENT ORIENTED CONTROL SYSTEM OF A MODULAR PARALLEL ROBOT FOR ELBOW REHABILITATION

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Abstract: *The paper focuses on the development of a control system for a parallel robot for medical rehabilitation of the elbow based on various Human Robot Interaction (HRI) approaches and torque monitoring capabilities for feedback from the robotic structure. The control system employs a set of predefined tasks specific to the medical rehabilitation task. To validate the proposed control system, several in-lab experimental tests are performed on healthy subjects.*

Key words: *parallel robot, torque control, HRI, robotic-assisted rehabilitation, brachial monoparesis.*

1. INTRODUCTION

Many neurological diseases and conditions affect a person's ability to function, which leads to limited involvement in the activities of daily living. According to the International Classification of Functioning, Disability and Health (ICF), disability is considered a health condition caused by illness, trauma or other situation that requires medical therapy in the form of personalized treatment by specialists. [1].

Monoparesis is a type of partial paralysis that affects only one limb (arm or leg). Total paralysis of on limb is called monoplegia [2]. Monoplegia is frequently caused by an injury to the cerebral cortex or spinal cord, multiple sclerosis, cerebrovascular injury or spinal tumors. Brachial monoparesis is an impairment of the stroke being the most common cause [3], leading to weakness, spasticity, numbness, paralysis, pain, and headaches.

One essential goal of brachial monoparesis therapy is the appropriate use of neuroplasticity for functional recovery. High-dose intensive training [4] and repetitive practice of certain functional tasks are critical for brachial monoparesis recovery.

The therapy for brachial monoparesis is made using repetitive rehabilitative motions of the impaired upper limb. The motion is performed partially by the patient and with the help of a kinetotherapist the motion is completed to full amplitude supported by the patient.

Due to repetitive characteristics of the brachial monoparesis therapy, the need to find solutions to provide better and more effective treatment for the patient and at the same time to aid the kinetotherapist during the rehabilitation process arise.

Robotic aided rehabilitation is an exercise-based therapy that use robotic devices to deliver highly repetitive, intensive, adaptable, and quantified physical training [5]. Robotic technologies can also lower the cost of medical care and make medical rehabilitation more affordable for a larger number of consumers. medical rehabilitation is available [6].

Qingcong and Hongtao [7] created an upper limb exoskeleton with kinematics consisting of 7 DOFs and 2 passive translation DOFs for rehabilitation training. For shoulder, elbow, and wrist rehabilitation, the exoskeleton robot is an open chain structure that resembles the anatomy of the human skeleton. The exoskeleton employs a closed-loop control system that runs on a real-time control platform designed in MATLAB, as well as the mechanism's dynamic model.

Paolucci et al. [8] describes a robotic device with end-effectors that can help patients with severe hemiplegia move while also supporting functional persons during upper limb rehabilitation. The device includes a visual feedback system which provides help in accomplishing daily tasks, targeting the rehabilitation of the shoulder and elbow motions.

This paper focuses on the control system of the ParReEx Elbow, A parallel robot has been developed for elbow rehabilitation with the aim of offering several HRI elbow rehabilitation methods depending on the patient's level of disability. HRI strategies are implemented by employing an inverse dynamic model and customizing several predefined functions with B&R's Mapp Motion technology [9].

The paper is organized as follows: Section II defines HRI strategies used in medical rehabilitation and presents medical protocols, followed by a brief description of the ParReEx Elbow robotic system and the development of control solutions for various rehabilitation strategies in Section III. Following experimental validation of the control system, Section IV describes how the HRI techniques are applied within the control system.

2. MEDICAL PROTOCOL FOR ROBOTIC ASSISTED REHABILITATION WITH HRI

Regarding to training modalities in robot assisted rehabilitation therapy Basteris et al. [10] presents eight modalities of Human Robot-Interaction (HRI):

- **Assistive**: it is necessary for the patient to move voluntarily. The robot helps the patient by providing partial weight support or forces that help the patient complete the task.
- **Active**: the robotic system just works as a measuring device and does not apply any force on the limb;
- **Passive**: the patient is not involved in the movement because it is carried out by the robot;
- **Passive-Mirrored**: a bimanual setup in which the unaffected limb guides (through an active device) the exact/mirrored passive movement of the affected limb;
- **Active-Assistive**: when the patient is not able to finish the initiated motion, a torque event is initiated, and the robotic device completes the exercise. Until the torque event the robot uses passive mode.
- **Corrective**: The robot stops the patient's movement when the error (distance from a target position) exceeds a certain threshold and instructs the subject to actively perform the rehabilitation exercise.
- **Path-guidance**: when a deviation occurs, the robot will aid the mobility along a defined course by executing corrections.
- **Resistive**: The robot applies force opposing the rehabilitation movement.

In the case of rehabilitation robots that involve human–robot interaction, the patient's safety the process of rehabilitation should be given the utmost importance. To improve the treatment safety aspect, the robot and human upper limb dynamics need be carefully and extensively evaluated [17–19]. The control system should be able to carry out the rehabilitation operation utilizing the information received from the dynamic behavior study while also communicating with the patient during the procedure to react to any departure from the initial rehabilitation plan. [11]. The range of motion (ROM)and motion types (Fig.1) are studied in order to properly develop the robotic system.

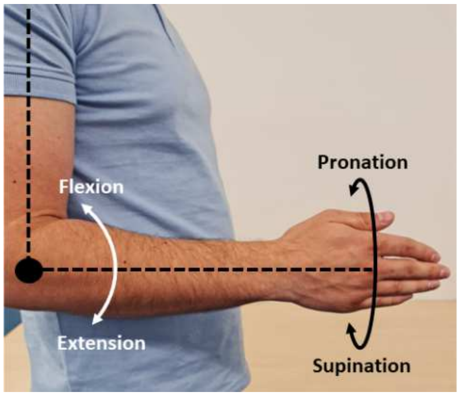


Fig.1. Elbow rehabilitation motions

Three rehabilitation motions are defined at the elbow level:

- **Elbow flexion**: The elbow is fully flexed, bringing the forearm over the arm.

- **Elbow supination**: With the palm pointed upwards, the forearm and hand are rotated.
- **Elbow pronation**: With the palm pointing down, the forearm and hand are rotated.

The values of motion amplitudes of the Elbow are summarized in Table 1 [12].

Table 1

Range of motion in degrees [°] for the elbow motions measured from the starting position [12]

Motion type	**Maximum Value**		**Mean Value**		**Minimum value**	
	Left	Right	Left	Right	Left	Right
Elbow flexion	**150**	**152**	**131.1**	**137.7**	**56**	**122**
Elbow pronation	**92**	**104**	**77.75**	**81.1**	**54**	**40**
Elbow supination	**100**	**128**	**84.55**	**81.55**	**60**	**62**

For the rehabilitation procedure a medical protocol must be defined by a physical therapist [12].

1. To begin rehabilitation, if the patient is in the acute phase, he must be conscious, hemodynamically stable, without fever and with CT / MRI confirmation of the brain injury (to exclude other diseases). In the subacute and chronic phases, the patient has a level of hemiparesis and the level on the segmental muscle strength scale are well known.
2. The physiotherapist evaluates the patient and establishes, based on the level of segmental muscle strength, the rehabilitation therapy, conditioned by the mobility of the limbs and the general condition of the patient.
3. Based on the initial data from point 2, the amplitudes of the robot's movement and the HRI mode are adjusted (Passive, Assistive, Active-Assistive and Resistive).
4. The patient is seated on a chair in an orthostatic position. This helps to focus on upper limb rehabilitation.
5. The patient is attached to the robotic device.
6. Based on the therapist's recommendations, the rehabilitation treatment is initiated in one of the following working modes: Passive, Assistive, Active-Assistive and Resistive for the Elbow rehabilitation motion (Flexion/Extension, Pronation/Supination).
7. According to the treatment program, the patient performs a series of exercises.
8. The device is removed at the end of the treatment.
9. Steps 2 through 8 are repeated for each rehabilitation session.
10. The exercises for the next session are modified based on the patient's progress as recorded by the robotic system.

3. THE PARALLEL ROBOT FOR ELBOW REHABILITATION

3.1. ParReEx-Elbow Description

ParReEx-Elbow (Fig.2) is a parallel robot designed to assist in elbow rehabilitation [13-16]. The robot has two degrees of freedom and is made up of the following components:

1. the flexion/extension motor.
2. the flexion/extension cylindrical gear unit.
3. the flexion/extension flange.
4. the flexion/extension connecting rod.
5. the pronation/supination motor.
6. flexible coupling.
7. Upper arm support.
8. Forearm support.
9. Cylindrical gear mechanism for pronation/supination motion.
10. Joystick.

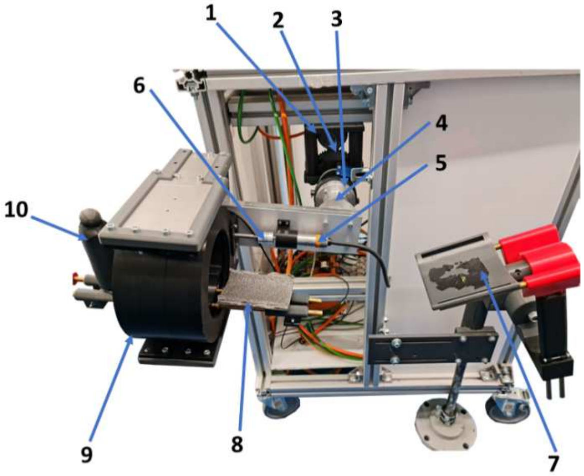


Fig.2. ParReEx Elbow experimental model

3.2. Control solution

The hardware configuration of the ParReEx Elbow parallel robot (Fig.3) is separated into three layers. The **User Level** comprises of a computer running Microsoft Visual Studio, Microsoft Access, Automation Studio [9], and the developed graphical user interface (GUI). **The Command-and-Control Level**, the second level consists of the PLC and the motor drivers. The third level, the **Physical Level**, includes the servomotors, the sensors used to set value to zero of the servomotors encoders (system initialization) and the mechanical frame of the ParReEx Elbow robot.

The transmission of data and commands from the **User Level** to the **Command-and-Control** level is accomplished through the use of the Easy Modbus (TCP/IP) communication protocol. The graphical user interface was created with Microsoft Visual Studio, Windows Forms, and C# as the programming language. The GUI includes the forms for Register, Login, Patient Data, and Exercise. The usernames and passwords are maintained in a Microsoft Access-based local database, while Automation Studio was used to develop the PLC software for the servomotors control.

The GUI operates the robotic system and connects with the PLC via the Modbus protocol while the elbow is receiving rehabilitation treatment. The servomotors and the proximity sensors are connected to the driver, which is controlled by the PLC. Powerlink communication is used to provide a bidirectional communication between the PLC, the drivers, and the servomotors.

The servomotors position, velocity, acceleration, and torque are monitored in real-time by the driver. The sensors are required to initialize the system (when the sensors are turned on, either performing a homing operation or changing the encoder value to 0) and their communication with the driver is unidirectional.

Patient Data (Fig.4) must be filled out by the user and include information about the patient.

The Exercises window (Fig.5) enables the user to setup the parallel robot for the rehabilitation operation while also monitoring the status of each axis and real-time position. In order to start the rehabilitation procedure, the following steps must be followed:

1. 1. Start the servos by clicking the "Start" button on the interface.
2. Initialize the system by pressing the "Homing" button. If the message in the upper right corner is yellow and shows the message "Robot stops", it means that the initialization process it's done. If it is red and the displayed message is "Error", it means that one or both actuators are malfunctioning and need to be reset with the "Error Reset" button. If the message is green and shows, "Robot is moving", the robot is performing one of the rehabilitation motions
3. Patient Selection.
4. HRI interaction mode according to patient health conditions.
5. Type of motion selection.
6. Insert motion amplitudes, velocity, and number of repetitions
7. After entering the data, press the "Start" button to start the movement. If the user wants to stop the movement, he or she can do so by pressing the "Stop" button. When users press the "Continue" button, the movement resumes from where it left off.

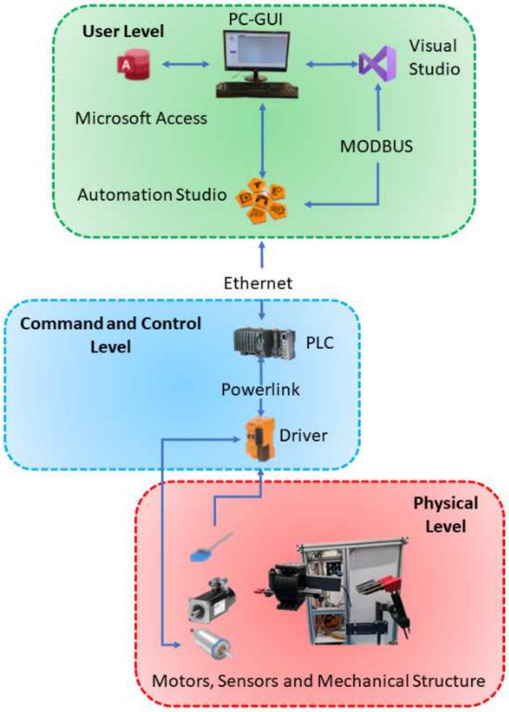
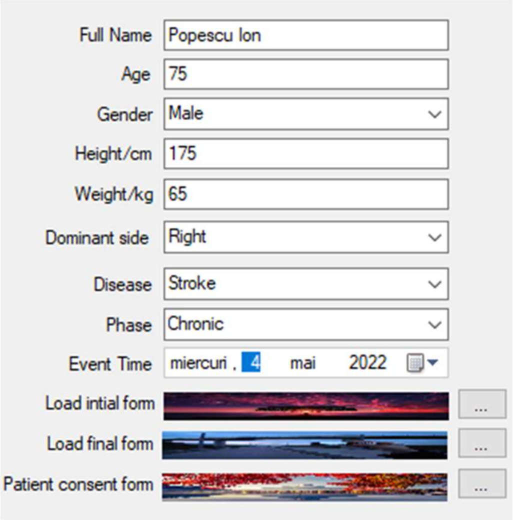


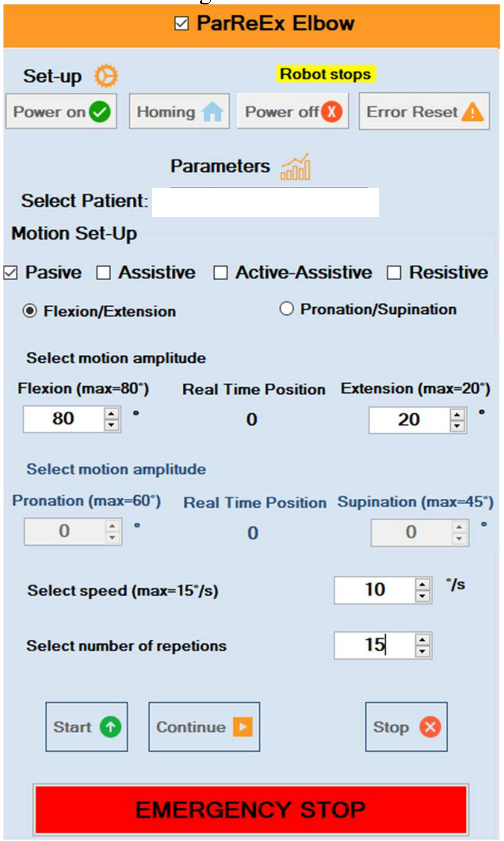
Fig.3. Hardware configuration of ParReEx Elbow

For safety issues, the GUI features a virtual "EMERGENCY STOP" button which stops the robot motion. When it is pressed, the rehabilitation motion cannot be resumed. All motion-related information, including motion type, amplitudes, speeds, and repetition rates, is stored in a database, which is used to track the patient's progress throughout the rehabilitation procedure.



Full Name	Popescu Ion
Age	75
Gender	Male
Height/cm	175
Weight/kg	65
Dominant side	Right
Disease	Stroke
Phase	Chronic
Event Time	miercuri , 4 mai 2022

Fig.4 Patient Data



Select Patient:

Motion Set-Up

☑ Pasive ☐ Assistive ☐ Active-Assistive ☐ Resistive

● Flexion/Extension ○ Pronation/Supination

Select motion amplitude

Flexion (max=80°)	Real Time Position	Extension (max=20°)
80 °	0	20 °

Select motion amplitude

Pronation (max=60°)	Real Time Position	Supination (max=45°)
0 °	0	0 °

Select speed (max=15°/s) 10 °/s

Select number of repetions 15

Fig5. Exercises window of GUI

4. IMPLEMENTATION OF HRI CONTROL AND EXPERIMENTAL RESULTS

4.1. HRI strategies implemented in ParReEx Elbow

By integrating HRI modalities into the control system, the rehabilitation process will be optimized, individualized care will be given based on the patient's level of disability, and the patient's recovery time will be reduced [20,21]. The HRI control modalities Passive, Assistive, Active-Assistive, and Resistive have been integrated in the ParReEx Elbow parallel robot.

In Fig.6 is presented the schematic representation of the control system of HRI interaction modes implementation.

The first HRI strategy implemented in the ParReEx Elbow is the **Passive** control modality. Without the patient's involvement, the robot completes the therapy motions. The invers dynamic model was used in this case by adding the arm weight to the robot weight. When the recorded torque exceeds the estimated torque, the robot stops and the user must select one of the following steps: Stop the motion, go back to safe (the robot goes back to its starting location), or continue from where it stopped.

The **Assistive** control strategy is used when the patient can perform the rehabilitation exercise independently. The robot task is to simply carry its own weight. This control strategy has been implemented using the inverse dynamic model, and the estimated torque was set as an input to a torque control function from Mapp Motion. If the feedback torque exceeds the estimated torque the robot will increase the velocity to maintain the estimated torque.

The third control modality developed is the **Active-Assistive** HRI method. The rehabilitation motion is initially started by the patient, and the robot just offers support by sustaining its own weight. The remaining repetitions are carried out passively if the subject is unable to complete the rehabilitation motion after the anticipated torque value is exceeded.

The **Resistive** mode is the fourth HRI strategy type that has been integrated. The inverse dynamic model was used with the mass of the robot slightly lighter from the real one (using a weight factor). The estimated torque computed is used as an input into a preconfigured function block. To drive the robot through the rehabilitative motion, the patient must exert effort on it (pull the joystick). If the feedback torque is lower than the estimated torque the robot will decrease velocity to maintain the estimated torque.

The Automation Studio add-on Mapp motion, created by B&R [9], makes it easy to integrate HRI with predefined functions like: MC_ReadActualTorque, MC_ReadActualPostion, MC_TorqueControl, and MpAxisBasic. These functions enable torque/position feedback from the servomotors and torque and position control for the servomotors while providing access to the axis parameters.

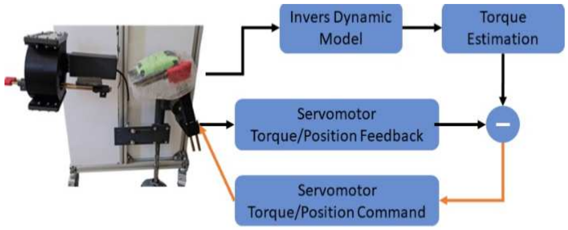


Fig.6. Control system schematic representation

4.2. Experimental data

Laboratory tests using 10 healthy subjects have been conducted to validate the HRI implementation utilizing the torque control function. The protocol described above has been used to perform the experiments. The subject has been placed in the rehabilitation chair, having the forearm fixed using a joystick in their hand. The rehabilitation motion parameters have been introduced using the GUI.

The recoded torques for the human-robot interaction modalities is presented in Fig. 7 for a flexion/extension motion and in Fig. 8 for a pronation/supination motion during rehabilitation exercises. The time history diagrams represent the average values for the 10 tested healthy subjects. A torque threshold has been set for each type of interaction as a safety measure as $T_{maxflexion}$ / $T_{maxextension}$ for the elbow flexion/extension motion and $T_{maxpronation}$/$T_{maxsupination}$.

When in the **Assistive** interaction mode (time history diagram in blue in Figs. 7 and 8), $T_{maxflexion} = 0.003$ Nm to $T_{maxextension} = -0.11$ Nm. The negative value shows that the robot is moving in the opposite direction. The motion is performed for the following chosen motion parameters: velocity = 10 °/sec and acceleration = 10 °/sec^2, and without payload.

When the **Active-assistive** is switched on, the torque (the black line in Figs. 7 and 8) gradually increases and when the torque limits are reached, the control system moves into the **Passive** mode. In this way, the patient is able (with help from the robot) to perform the motion (in terms of motion range). The same plot shows that the healthy subject can completely perform the extension motion (in terms of motion range), the torque being below the set limit for this type of motion.

The **Passive** mode (the red line in Figs. 7 and 8) is entirely performed by the robot, with no input from the patient. The imposed torque thresholds (-0.23 and -0.12 Nm) are used as a safety measure, which means that the robot stops (emergency stop) if these values are reached.

The **Resistive** mode (the orange dotted line in Figs. 7 and 8) also uses two thresholds (-0.087 and 0.007 Nm). It is obvious that during the rehabilitation process, the torque evolution is steadily increasing, suggesting that the robot is opposing the patient's movement. The robot returns to its starting position and the procedure is finished when the torque decreases.

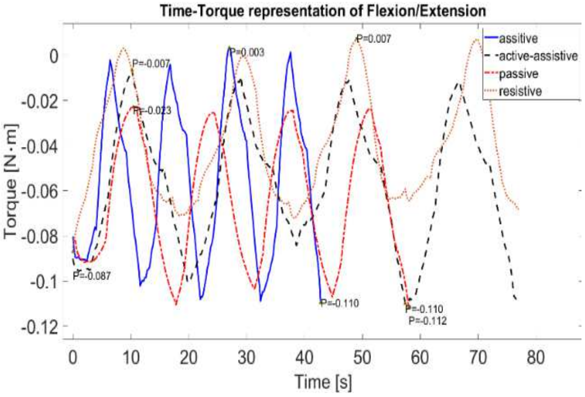


Fig.7. Torque evolution during the flexion/extension rehabilitation

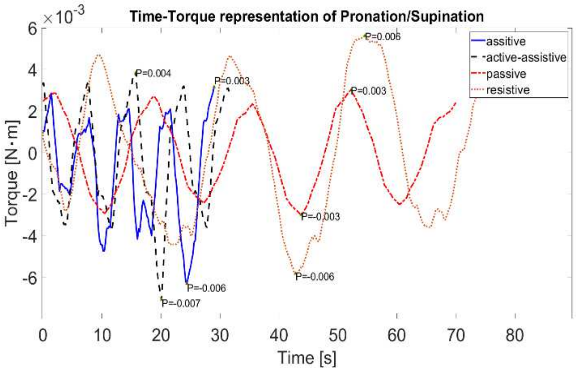


Fig.8. Torque evolution during the pronation/supination rehabilitation

5. CONCLUSION

The control system of the ParReEx Elbow has successfully integrated four human-robot interaction modes. A series of lab tests with healthy subjects were conducted after the development and integration of human-robot interaction techniques to validate and show the system's functionality. The tests carried the system to the next stage of development and prepared for upcoming clinical tests by demonstrating the functionality of the established control system. Torque-based control also makes robotic rehabilitation therapy more user-friendly while improving patient safety.

6. AKNOWLEDGEMENT

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SISTEM DE CONTROL ORIENTAT PENTRU PACIENT AL UNUI ROBOT PARALEL MODULAR PENTRU REABILITAREA COTULUI

Lucrarea se concentrează pe dezvoltarea unui sistem de control pentru un robot paralel pentru recuperarea medicală a cotului bazat pe diverse abordări Human Robot Interaction (HRI) și capacități de monitorizare a cuplului pentru feedback de la structura robotică. Sistemul de control utilizează un set de sarcini predefinite specifice sarcinii de recuperarea medicală. Pentru validarea sistemului de control propus, sunt efectuate mai multe teste experimentale în laborator pe subiecți sănătoși.

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