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EMERGING TECHNOLOGIES IN PERSONALIZED TREATMENT FOR ROBOTIC ASSISTED UPPER LIMB REHABILITATION

Radu MORARIU-GLIGOR, Dragoş SEBENI, Călin VAIDA, Alina CIUPE, Ionut ULINICI, Daniela JUCAN, Iuliu NADĂŞ, Doina PÎSLĂ

Abstract: *This paper presents the emerging technologies that can be used in upper-limb rehabilitation after stroke. In addition, the upper-limb functionalities that can be regained through rehabilitation are defined. The field of robot-assisted rehabilitation is developing rapidly; therefore, a series of robot structures created for upper-limb rehabilitation are described, specifying the functionalities they address.*
Keywords: *Emerging technologies, upper limb rehabilitation, robotic-assisted therapy.*

1. INTRODUCTION

In Europe, more than 1.5 million people suffer a stroke each year, which poses a challenge for healthcare systems and an ever-increasing demand for rehabilitation technologies.

The use of emerging technologies can represent a step forward in personalizing upper-limb rehabilitation treatments. Technologies with the potential to improve the rehabilitation paradigm include [1]:

- robot-assisted therapy (RAT);
- virtual reality (VR) and augmented reality (AR);
- artificial intelligence (AI) and machine learning (ML);
- non-invasive brain stimulation;
- telerehabilitation.

In robot-assisted therapy, robots interact with the patient and provide support for training specific body parts; the movements can be precise, of predefined intensity, and performed repetitively over a predefined number of cycles. The use of robots offers the advantage of enforcing predefined movements specific to the functionality of the affected limb, allowing control of both motion and the generated or resisted force, while also encouraging motor relearning.

By using virtual reality (VR) and augmented reality (AR), immersive, interactive environments are created that stimulate and motivate the patient, thereby reducing rehabilitation time. With the help of these technologies, a range of real-world scenarios is simulated in which the patient can practice different movements.

Through the use of artificial intelligence, rehabilitation therapy can be personalized, the developed algorithms can adjust the level of assistance in real time based on data regarding patient needs correlated with their progress. AI algorithms use and analyze large datasets and by correlating them with data received from sensors, adjust therapy parameters in real time: imposed trajectories, movement intensity, generated or imposed force, difficulty level, etc. Machine learning enables decoding of the patient's intentions based on acquired bioelectrical signals (EMG, EEG), thus contributing to the control of the robotic devices used. Non-invasive brain stimulation is an adjuvant therapy in neuromotor rehabilitation, through which neural networks are modulated and neuroplasticity is enhanced.

The technologies presented above operate on data acquired from a range of sensors that can be mounted on the body (e.g., accelerometers,

IMUs, EMG, etc.), thereby tracking muscular activity, trajectories, and movement amplitudes. Data monitoring can also be performed remotely, reducing the time the patient spends in the clinic, as rehabilitation can be carried out at home as well. Using remote communication technologies, therapists can monitor the patient's activity and adjust the therapy.

A new paradigm is proposed for upper-limb rehabilitation after stroke, as shown in Figure 1 [2]. According to this paradigm, new therapies will use robots, will be personalized and adapted to the patient's needs and cognitive abilities, will continuously monitor the patient's status and progress, and treatment will be delivered using artificial intelligence algorithms. Treatment can be performed both in hospitals or specialized clinics and at the patient's home, with therapists able to follow and intervene supporting thus the paradigm of tele-rehabilitation.

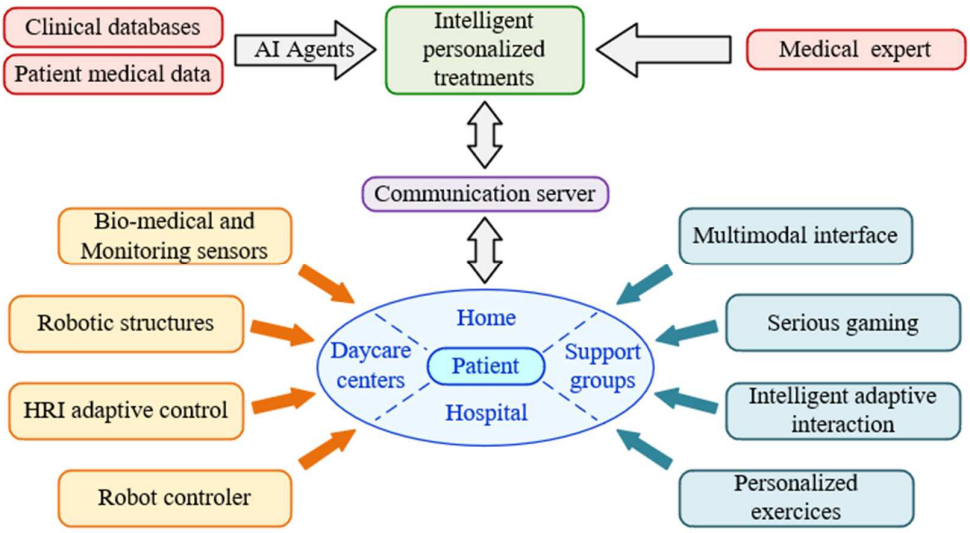


Fig. 1. Patient-centered robotic rehabilitation system with adaptive interaction and data processing capabilities

MOTIVATION: The aim of this paper is to establish the rehabilitation needs of the upper limb and to present technical solutions appropriate for this purpose. To this end, a number of scientific papers and analyses regarding upper-limb rehabilitation for patients with neuromotor disabilities were reviewed.

The paper is structured as follows: Section 2 presents the upper limb functionalities, Section 3 presents some aspects regarding the use of emerging technologies in neurological rehabilitation, and Section 4 presents several robotic structures developed for upper-limb rehabilitation that can be integrated with the emerging technologies presented above.

2. DEFINITION OF UPPER-LIMB FUNCTIONALITIES

It is estimated that the upper-limb account for 54% of the functions of the entire body, therefore restoring upper-limb functionality is very important. Rehabilitation aims to restore grasping capability (prehension), mobility, sensitivity, and coordination, with the objective of ensuring independence in activities of daily living (ADL).

From the perspective of upper-limb rehabilitation, it is important to recover the following functions:

- joint mobility: consisting of performing flexion, extension, and ulnar/radial deviation movements both at the wrist and at the metacarpophalangeal (MCF) and interphalangeal (IFP) joints, with the role of correctly positioning the hands and fingers;
- muscle strength and endurance: defines muscular power at the level of the intrinsic and extrinsic muscles of the hand and forearm, important for manipulating objects of different sizes and weights;

- prehension (grasping): a vital function that includes various types of grip: power grip (squeezing an object), precision grip (picking up small objects), lateral grip (holding a key);
- coordination and dexterity: refers to the ability to perform precise and controlled movements;
- sensory function (sensitivity): recognition of textures, temperatures, and shapes, and provision of proprioceptive feedback;
- motion control: the ability to initiate, control, and stop movements continuously and intentionally;
- functional integration in activities of daily living (ADL): ensures the patient's autonomy or independence by enabling hand functionality for self-care (feeding, dressing, personal hygiene) and by ensuring the ability to perform professional and recreational activities (handling tools, practicing sports).

An AHP (Analytical Hierarchy Prioritization) was conducted among seven critical upper limb rehabilitation requirements, the result being illustrated in Figure 2.

The analysis illustrates that rehabilitation should focus first on reestablishing motion control followed by the sense of touch (the sensory function).

These two requirements must receive over 50% of the effort of regaining control of the lost functionality for the upper limb.

Group
VOC
VOC AHP Prioritization

Is the row item

- more important (>1),
- equally important(1), or
- less important (<1)

compared to the column item?

Consistency

	VOC2 Muscle Strength and Endurance	VOC3 Prehension (Grasping)	VOC4 Coordination and Dexterity	VOC7 Functional Integration in ADL	VOC1 Joint Mobility	VOC5 Sensory Function	VOC6 Motion control	VOC2 Muscle Strength and Endurance	VOC3 Prehension (Grasping)	VOC4 Coordination and Dexterity	VOC7 Functional Integration in ADL	VOC1 Joint Mobility	VOC5 Sensory Function	VOC6 Motion control	Importance in Group	Minimum	Maximum
VOC2 Muscle Strength and Endurance	1	1/2	1/2	1	1/2	1/3	1/3	7%	4%	5%	10%	7%	6%	10%	7%	4%	10%
VOC3 Prehension (Grasping)	2	1	1/2	1/2	1	1/2	1/3	14%	9%	5%	5%	13%	9%	10%	9%	5%	14%
VOC4 Coordination and Dexterity	2	2	1	1/2	1/2	1/2	1/3	14%	17%	9%	5%	7%	9%	10%	10%	5%	17%
VOC7 Functional Integration in ADL	1	2	2	1	1/2	1/2	1/3	7%	17%	18%	10%	7%	9%	10%	11%	7%	18%
VOC1 Joint Mobility	2	1	2	2	1	1/2	1/2	14%	9%	18%	20%	13%	9%	15%	14%	9%	20%
VOC5 Sensory Function	3	2	2	2	2	1	1/2	21%	17%	18%	20%	27%	19%	15%	20%	15%	27%
VOC6 Motion control	3	3	3	3	2	2	1	21%	26%	27%	30%	27%	38%	30%	28%	21%	38%
Consistency Ratio	0.043																
N	7																
Consistency (Lamda - N):	0.35																
Respondent 1																	

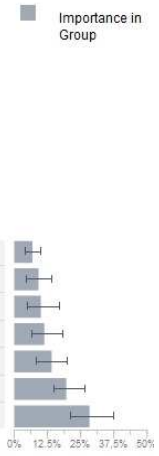


Fig. 2. AHP (Analytical Hierarchy Prioritization) analysis of hand functionalities

3. ASPECTS REGARDING THE USE OF EMERGING TECHNOLOGIES IN NEUROLOGICAL REHABILITATION

Technologies such as robotics, virtual reality, artificial intelligence, non-invasive brain stimulation, and telerehabilitation - used alone or in combination - can provide therapy techniques both in clinical and community settings [1][3][4].

Neurorehabilitation is a complex process through which a person recovers after an illness or a physical, physiological, or mental disorder. The goal is the (partial or complete) restoration of affected capacities and functionalities, which may be neurological (speech, swallowing, memory or attention deficits, reading, writing) or physical (limb control, strength, balance, or gait). Rehabilitation protocols use specific training procedures that involve exercises of adapted intensity with task-specific demands.

Stroke is the leading cause of acquired disability in adults, with most patients having a residual deficit in fine motor control of the upper limb.

A. Robot-assisted therapy (RAT)

Robot-assisted therapy can be delivered using robotic devices that generate limb movement,

end-effector robots (distal and proximal, unilateral or bilateral) that interact with the patient at the level of the hand or forearm, or exoskeletons that assist patients with multiple mobility impairments [6][7]. Robotic devices may have one or more degrees of freedom, they are connected either at the arm and/or forearm level and provide mechanical constraint of the affected segment. Exoskeletons reproduce human limb kinematics and support movement by controlling the position and orientation of each joint. Paper [7] presents an analysis of the state of design, control, construction, as well as the main manufacturers of robots for upper-limb rehabilitation. The use of robots offers the advantage of enforcing predefined movements (repetitive and intensive) specific to the functionality of the affected limb, allowing control of both motion and the generated or resisted force, while also encouraging motor relearning [6]. Research has shown that there are no significant differences in upper-limb rehabilitation outcomes among existing robot types, with no conclusive evidence in favor of one device over another [1].

To increase the potential of robots in neurorehabilitation, robotic therapy can be combined with other types of therapies: artificial intelligence (AI), virtual reality (VR), and telerehabilitation (TR) [7].

B. Virtual reality and augmented reality

Using VR, complex systems can be created based on learning by imitation, tracking a series of patient parameters such as posture, joint mobility, muscle strength, balance, or gait [3][4]. Virtual reality (VR) can improve neuroplasticity and post-stroke recovery by enabling more intensive training (tasks with different difficulty levels), standardized yet enhanced (based on recorded feedback), as well as safe and engaging for the patient (by simulating real-life scenarios) [1][8].

The development of VR technology has led to other related technologies that improve user–environment interaction, such as augmented reality (AR) and mixed reality (MR). Mixed reality (MR) is a combination of VR and AR that creates dynamic interactions between virtual and real objects [12]. An application is presented in [13], where a haptic device is used to solve a Sudoku game.

The advantages of VR systems include simulation of the real environment, reduced perception of pain and unpleasant experiences, adaptive feedback, easy learning of tasks, generation of scenarios that would be difficult to simulate in real life, low costs, and no significant adverse effects [9]. The disadvantages of these devices are related to movement limitations (limited maneuvering space), dependence on supervisors, or patient's adaptation to the technology used. Patients may experience motion sickness symptoms, dizziness, ocular or physical fatigue, as well as nausea.

Most studies suggest positive results, VR being a feasible and effective tool for alleviating pain and anxiety or for physical and neurological rehabilitation [10][12]. Future VR applications based on emerging technologies will be predictive, preventive (analyzing the patient's medical history and specialists recommendations), personalized, and participatory (increasing patient engagement and information exchange). VR can also be useful for training therapists: correct movements are performed by the therapist, recorded with motion sensors, and imported into simulation scenarios.

C. Artificial intelligence and machine learning:

With the help of artificial intelligence and machine learning, useful tools can be developed in the rehabilitation process: voice assistants, intelligent screen readers, image recognition systems, easy-to-use interfaces for patients with disabilities, applications, etc.

D. Non-invasive brain stimulation:

The development of information technologies, bioengineering, and neuroscience has enabled significant progress in neurorehabilitation through brain–computer interfaces (BCIs). A brain–computer interface (BCI) is a device that translates central nervous system (CNS) signals into command signals for an external device (a computer or other electronic devices) [4][10]. Non-invasive methods used to record brain activity in BCI

applications include electroencephalography (EEG), magnetoencephalography (MEG), functional near-infrared spectroscopy (fNRIS), and functional magnetic resonance imaging (fMRI) [5]. Transcranial neural stimulation is a new technology within the BCI spectrum for rehabilitation and can be performed through transcranial magnetic stimulation (TMS) and transcranial direct current stimulation (tDCS).

However, future work must address the following issues: which diseases are suitable for the technology, the post-injury time point at which it should be applied, the consistency of results, the patient's experience when using the equipment, etc. [9][10].

E. Telerehabilitation:

The effectiveness of neurological rehabilitation treatments depends largely on treatment consistency, timely delivery of treatment, patient motivation (which depends on achieved progress), as well as the attractiveness of treatment methods, participating in procedures in a familiar environment constitutes an incentive.

Telerehabilitation (TR) is based on the use of telecommunication devices (mobile phones, tablets, video cameras) that provide logistical facilities for both therapists and patients, with the aim of delivering rehabilitation services at home [1]. Information technologies enable patient monitoring both via electronic devices (webcams, sensors, data transfer) and via online questionnaires and diaries, as well as video recordings of treatment sessions [3][11][12].

The presented technologies can provide more intensive training and have demonstrated functional improvement beyond the normal recovery period. Technologies such as RAT, VR, and TR have proven to be at least as effective as conventional therapy [1].

Instead of conventional treatments delivered in hospitals or medical centers, future rehabilitation will more likely be home-based, personalized, assessed and monitored via telecommunication systems, automated, and self-administered by patients [11].

4. SOLUTIONS REGARDING ROBOT-ASSISTED THERAPY FOR UPPER LIMB REHABILITATION

The impact of new technologies lies in increasing the degree of adaptation to patient needs, reducing duration and increasing treatment efficiency, and delivering home-based treatment with remote assistance.

A five-step methodology to incorporate real-time patient feedback and monitoring of patient status into the rehabilitation process is proposed in [14] (Fig. 3):

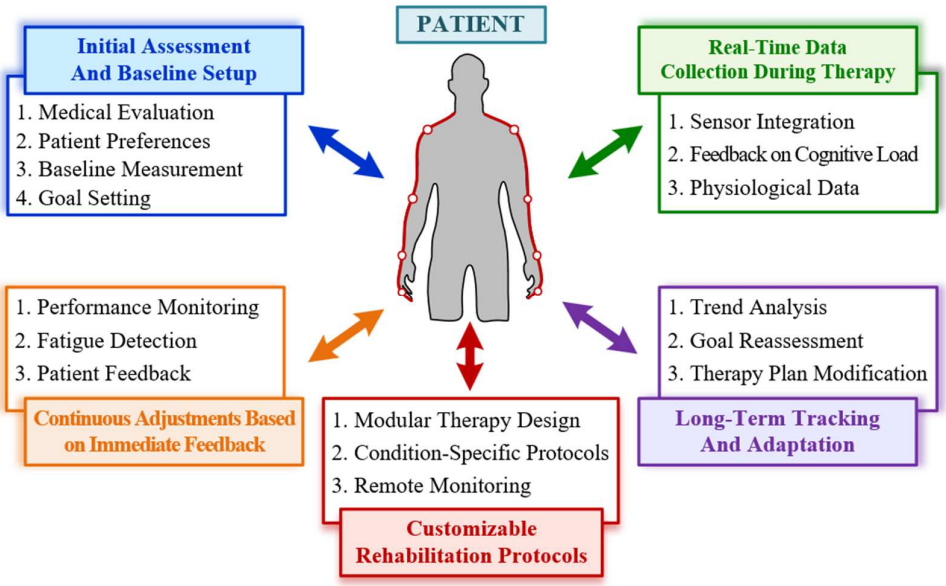


Fig. 3. Methodology for Personalizing Robotic-Assisted Rehabilitation with Real-Time Feedback

- Initial assessment and baseline setup: collecting data on the patient's physical and psychological status;
- Real-time data collection during therapy: necessary to capture patient performance and dynamically adjust exercises;
- Continuous feedback-based adjustments: aim to dynamically adjust therapy during each session, based on the patient's real-time performance, to optimize the difficulty level;
- Long-term monitoring and adaptation: ensures that the rehabilitation process evolves as the patient progresses, benefiting from adjustments to the treatment plan;
- Personalized rehabilitation protocols: adapting rehabilitation protocols according to the patient's progress, preferences, and clinical status.

Specialists from the Research Center for Industrial Robots Simulation and Testing (CESTER) of the Technical University of Cluj-Napoca have developed several constructive variants of robots for upper-limb neurorehabilitation.

First, an extensive survey (papers published between 2002 and 2024) was carried out regarding the development of robots for upper-limb rehabilitation, focusing on their mechanical design, mobility, and actuation systems [15]. This enabled the identification of potential benefits of using robots in rehabilitation treatment. Using anthropometric models of the human body, the required types of movements and their ranges were determined, and the lengths and masses of limb segments were quantified [16]. Based on the obtained data, medical protocols for post-stroke patient rehabilitation were proposed, correlated with the most recent clinical studies.

4.1 Spherical parallel robot for upper limb rehabilitation – ASPIRE

Based on the theoretical and practical considerations presented above, a prototype of an upper-limb rehabilitation device, called ASPIRE, was developed [17][18][22]. The shoulder and forearm joints are targeted, reproducing the movements required in rehabilitation therapy (Fig. 4) [19]:
- shoulder flexion/extension (±80°);
- shoulder abduction/adduction (±80°);
- forearm pronation/supination (±80°).

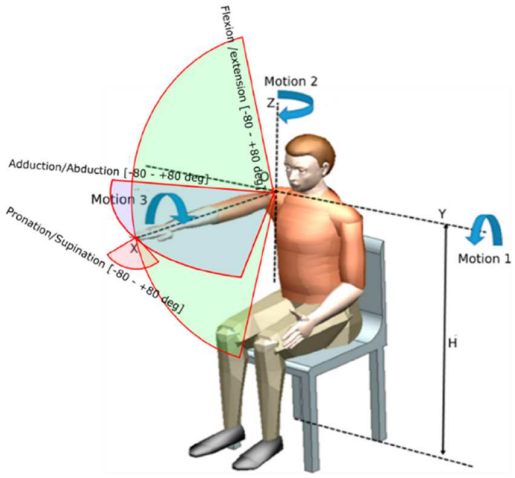


Fig. 4. The targeted motion of ASPIRE [19].

The robot has a spherical structure with two degrees of freedom (DOF), with a parallel architecture that enables efficient motion generation throughout the entire workspace. After the prototype was built, the ASPIRE robot underwent a clinical evaluation, and based on data collected from sensors, patients, and physicians, the robot was adjusted, resulting in an improved version [19].

The experimental model of the ASPIRE robot is shown in Fig. 5 [19].

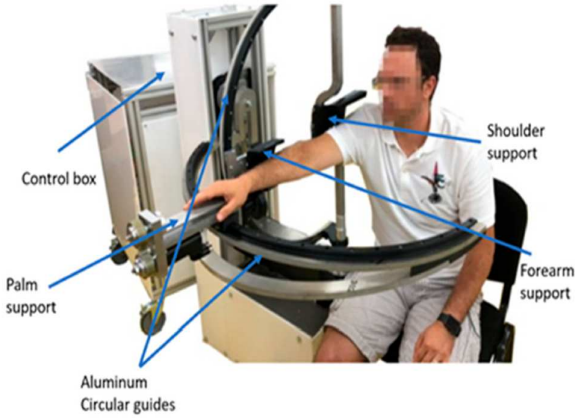


Fig. 5. Initial experimental model of ASPIRE [19]

The control architecture of the ASPIRE robot is illustrated in Fig. 6 [19].

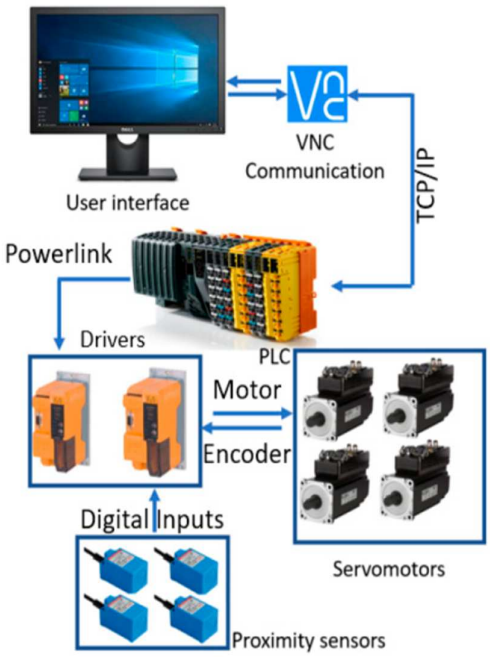


Fig. 6. Control arhitecture of ASPIRE [19]

4.2 Spherical parallel robot for elbow rehabilitation – ParReEx Elbow

The ParReEx Elbow parallel robot (Fig. 7) is designed for elbow rehabilitation.

The robotic system has two degrees of freedom (DOF) and can perform the following rehabilitation movements:
- elbow flexion/extension;
- forearm pronation/supination.

The patient's arm is immobilized via three anchoring points in the rehabilitation module, located on the upper arm, forearm, and the patient's hand [20].

The use of sensors (position, force or moment, muscle activity) can provide information regarding the patient's activity and progress.

The system can be controlled based on an artificial intelligence algorithm, so as to ensure a personalized treatment, as appropriate as possible to the patient's needs.

4.3 Spherical parallel robot for wrist rehabilitation – ParReEx Wrist

This is a parallel robot designed for safe, personalized wrist rehabilitation for stroke patients, offering modes like passive, active-assistive, and resistive training to help regain motor function (see Fig. 8).

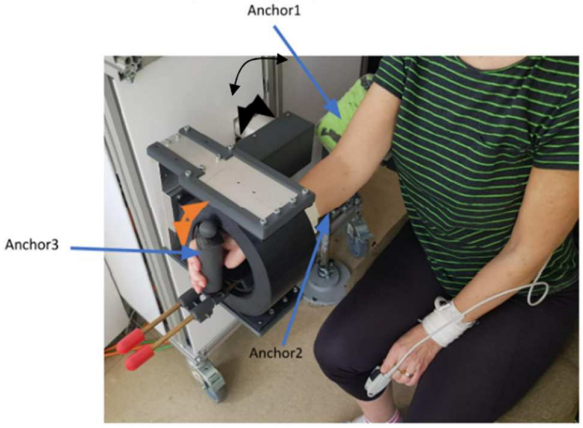


Fig. 7. The ParReEx Elbow robotic system [20]

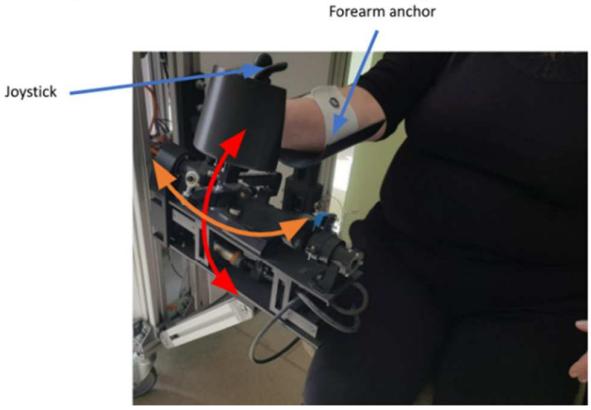


Fig. 8. The ParReEx Wrist Robotic System [20]

The rehabilitation movements it can perform are: - wrist flexion/extension; - wrist adduction/abduction.

During the rehabilitation exercise, the patient must use the right hand to grasp the joystick of the rehabilitation module. Hand anchoring is performed at the wrist, which is immobilized using an elastic Velcro strap.

The movements can be controlled by motors, and the movements are monitored by sensors. The robot can be integrated into a system controlled by intelligent algorithms, which can monitor the patient's progress.

4.4 Robot for functional recovery of the hand

Functional recovery of the hand (fingers) is a complex process, essential for patients with neuromotor impairments of various etiologies.

The customized flexible robot for recovering human hand movements is designed to perform

finger flexion and extension movements independently, with a high degree of precision. The central innovative element consists in customizing each component according to the patient's anthropometric characteristics, so that the robot integrates optimally on the user's hand. Each finger is equipped with a component manufactured as a single piece, obtained through 3D printing with photopolymerization technologies, which allow the combination of flexible materials with rigid elements in a single assembly. The flexible part reproduces the anatomical shape of the finger, while the rigid elements are positioned at the phalanges to ensure stability and correct guidance of movement.

At the level of each finger, the robot includes:

- a customized flexible component adapted to the patient's finger dimensions and shape;
- integrated rigid elements that locally stiffen the phalanges and ensure controlled transmission of forces;
- channels and tubular elements that guide the actuation tendons used for flexion and extension movements.

Each finger's motion is achieved via two tendons: one dedicated to flexion and one dedicated to extension. These tendons are guided through components placed at the palm and wrist level, with the role of organizing and protecting the actuation paths (Fig. 9 and Fig. 10). The robot can reproduce complex functional movements, such as grasping objects with one or multiple fingers or the thumb opposition movement. The customized flexible robot for recovering human hand movements can be extended by integrating an artificial intelligence system that enables automatic adaptation of therapy to the functional particularities of each patient. Each customized flexible component at the finger level is monitored using position and deformation sensors embedded in the flexible material.

Artificial intelligence continuously analyzes these data to determine:

- the flexion and extension angle of each phalanx;
- the actual movement amplitude compared to the amplitude imposed by the robot;
- the uniformity and continuity of the movement.

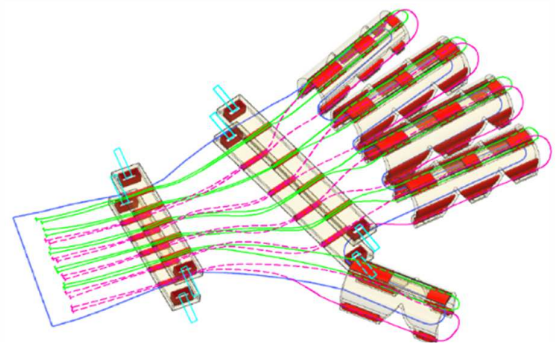


Fig. 9. Finger extension movement

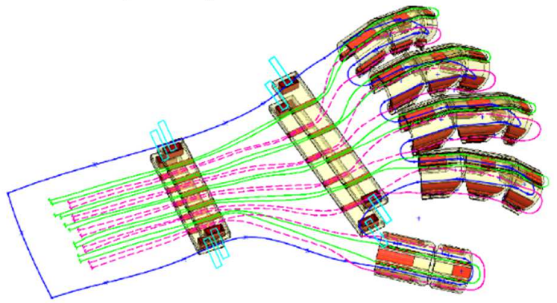


Fig. 10. Finger flexion movement

Based on this information, AI algorithms can automatically identify mobility limitations, joint blockages, or asymmetric movements between fingers, providing an objective assessment of hand function.

The intelligent robot can be extended by using muscle activity sensors (EMG) placed on the forearm. Artificial intelligence analyzes EMG signals and correlates them with the actual finger movement, determining the degree of active patient involvement.

In this way, the system can distinguish between:

- passive movements, performed exclusively by the robot;
- assisted movements, in which the patient contributes partially;
- active movements, performed predominantly by the patient.

Based on this information, the robot automatically adjusts the level of assistance, encouraging active recovery and stimulation of neuroplasticity.

4.5 Use of collaborative robots

Paper [21] presents an upper-limb rehabilitation robotic system using collaborative robots; the opportunity to use them is enabled by characteristics such as safety and ease of use, flexibility, precision, and consistency.

The study presents two use cases within task-oriented training exercises defined according to the patient's specific requirements, using two-dimensional (2D) and three-dimensional (3D) predefined trajectories, respectively.

For training using the two-dimensional trajectories, an exercise involving solving a maze was selected. Figure 11 illustrates the communication diagram between the hardware and software equipment used to define the 2D rehabilitation trajectory.

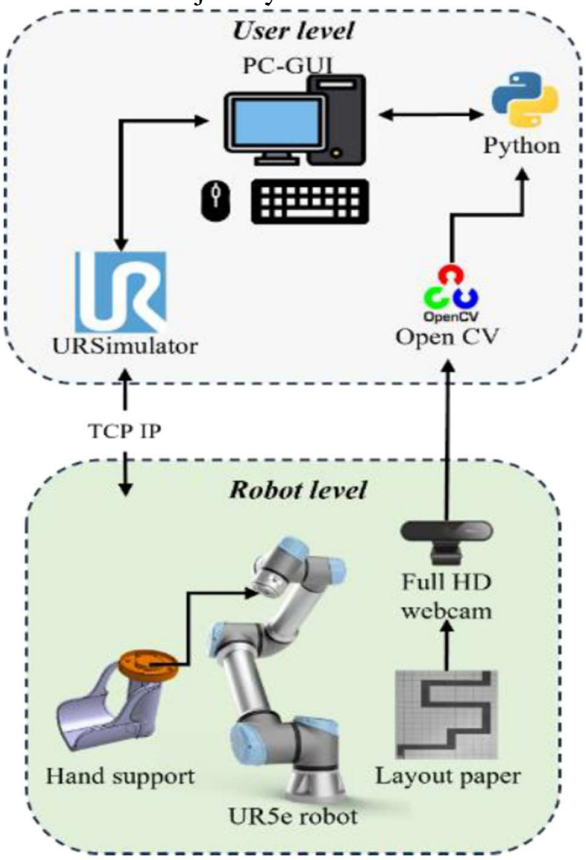


Fig.11. Communication diagram between hardware and software equipment used to perform the 2D rehabilitation trajectory definition [21]

A rehabilitation exercise designed to generate a 3D motion trajectory uses a tracking system (OptiTrack) that captures data from markers attached to a rigid body held by the physician/therapist and transfers them to the robot end-effector, which reproduces the therapist's movements using a predefined scale. The signals transmitted by the physical therapist via the OptiTrack system cameras to the robot end-effector are converted using programs developed in Matlab and Python.

The flowchart showing how the data captured from the physical therapist are transmitted to the robot end-effector is presented in Figure 12.

5. CONCLUSIONS

Although a series of neurorehabilitation robots have been developed recently, the field is still evolving rapidly. The paper presents a series of robotic structures for upper limb rehabilitation, including hand rehabilitation. Analyzing the functionalities that need to be restored for upper limb rehabilitation, it was found that movement control and sensory function are very important. The presented structures offer a complete solution regarding upper limb rehabilitation. Future studies should focus on developing lightweight robots suitable for home use and enabling activities similar to activities of daily living (ADL).

Robot command and control systems will need to be developed using artificial intelligence and machine learning algorithms based on large datasets. In addition, the developed mechatronic structures and treatment schemes will need to be flexible to ensure personalization according to the degree of impairment and the patients' characteristics and preferences. Last but not least, the cost price will have to be affordable.

6. ACKNOWLEDGMENT

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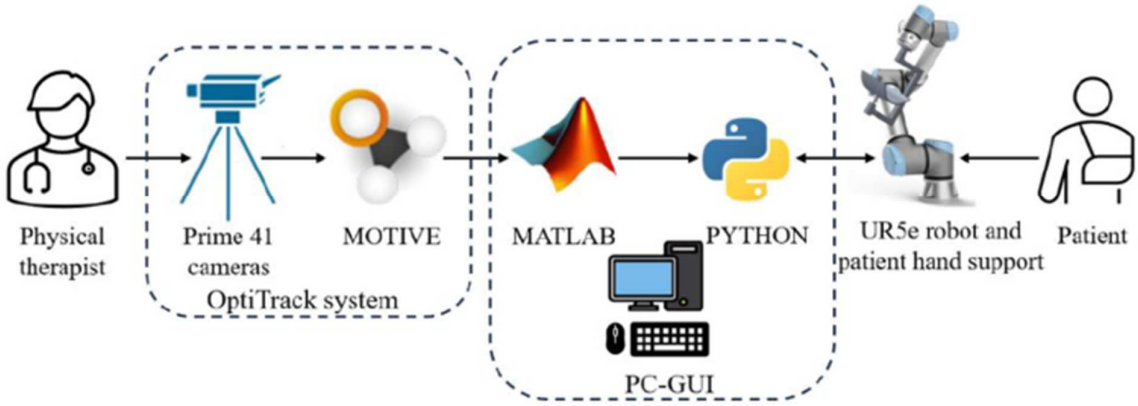


Fig. 12. Data transfer flowchart from the physical therapist to the patient [21]

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Tehnologii emergente în tratamentul personalizat pentru reabilitarea asistată de robot a membrelor superioare

Rezumat: Lucrarea prezintă tehnologiile emergente care pot fi utilizate în reabilitarea membrelor superioare după un accident vascular cerebral. De asemenea, sunt definite funcţionalităţile membrului superior care pot fi redobândite prin reabilitare. Domeniul reabilitării asistate de roboţi este în plină dezvoltare, de aceea sunt descrise o serie de structuri de roboţi creaţi pentru reabilitarea membrului superior, cu specificarea funcţionalităţilor cărora se adresează.

Radu MORARIU-GLIGOR, PhD, Assoc. Prof. Eng., CESTER - Research Center for Industrial Robots Simulation and Testing, Technical University of Cluj-Napoca, Radu.Morariu@mep.utcluj.ro, +40 264 401 654, 103-105 Muncii Blvd., Cluj-Napoca, Romania.

Dragoş SEBENI, PhD student, CESTER - Research Center for Industrial Robots Simulation and Testing, Technical University of Cluj-Napoca, Dragoş.Sebeni@mep.utcluj.ro, +40 264 401 684, 103-105 Muncii Blvd., Cluj-Napoca, Romania.

Calin VAIDA, PhD, Professor Eng., CESTER - Research Center for Industrial Robots Simulation and Testing, Technical University of Cluj-Napoca, Calin.Vaida@mep.utcluj.ro, +40 264 401 684, 103-105 Muncii Blvd., Cluj-Napoca, Romania.

Alina CIUPE, Ec., Technical University of Cluj-Napoca, Alina.Ciupe@ethm.utcluj.ro, +40 264 401 230, 103-105 Muncii Blvd., Cluj-Napoca, Romania.

Ionuţ ULINICI, PhD, Engineer, CESTER - Research Center for Industrial Robots Simulation and Testing, Technical University of Cluj-Napoca, Ionut.Ulinici@omt.utcluj.ro, +40 264 401 684, 103-105 Muncii Blvd., Cluj-Napoca, Romania.

Daniela JUCAN, PhD, Assist. Prof. Eng. Ec., CESTER - Research Center for Industrial Robots Simulation and Testing, Technical University of Cluj-Napoca, +40 264 401 684, Daniela.Jucan@mis.utcluj.ro, 103-105 Muncii Blvd., Cluj-Napoca, Romania.

Iuliu NADĂŞ, PhD, Engineer, CESTER - Research Center for Industrial Robots Simulation and Testing, Technical University of Cluj-Napoca, Iuliu.Nadas@itim-cj.ro, +40 264 401 684, 103-105 Muncii Blvd., Cluj-Napoca, Romania.

Doina PÎSLĂ, PhD, Professor Eng., **Corresponding author**, CESTER - Research Center for Industrial Robots Simulation and Testing, Technical University of Cluj-Napoca, Doina.Pisla@mep.utcluj.ro, +40 264 401 684, 103-105 Muncii Blvd., Cluj-Napoca, Romania.