Upper-Limb Robotic Exoskeletons for Stroke Rehabilitation: A Comprehensive Review, Comparative Classification, And Design Guidelines

Luis Vázquez-Sánchez, Manuel Arias-Montiel, Manuel Adam-Medina, and Carlos Daniel García-Beltrán

Abstract— **This paper presents a structured review of upper-limb robotic exoskeletons for post-stroke rehabilitation, focusing on mechanical design principles, biomechanical compatibility, control strategies, actuation systems, and mechanical human–machine interfaces. State of the art developments were analyzed through major scientific databases and classified according to degrees of freedom, portability, sensing modalities, and rehabilitation objectives. The review highlights current design trends, limitations in commercial systems, and challenges related to kinematic alignment, workspace validation, and ergonomic integration.Based on the identified research gaps, particularly in cost-effectiveness, portability, and anthropometric adaptability—a 5-degree-of-freedom upper-limb exoskeleton, is presented as a case oriented design proposal. The architecture incorporates forward and inverse kinematic modeling to ensure compatibility with physiological ranges of motion of the shoulder, elbow, and wrist. Lightweight materials such as Polyoxymethylene and aluminum are considered to reduce distal inertia and improve wearability. This work contributes a comparative classification framework and biomechanically grounded design guidelines aimed at facilitating accessible and scalable neurorehabilitation technologies.**

Link to graphical and video abstracts, and to code: https://latamt.ieeer9.org/index.php/transactions/article/view/10072

Index Terms— **Upper-limb exoskeleton, Stroke rehabilitation, Robotic rehabilitation review, Assistive technology, Workspace optimization, Human machine interface**

I. Introduction

THE analysis of the data corresponding to 2023 to the present, included in the World Morbidity Burden that was carried out for this report, allows us to estimate that 16% of the world population (about 1 300 million people of the total population, estimated at 8125 million in 2025) had a "moderate or severe disability". The UN report highlights that only 28-34% of people with severe disabilities receive social benefits [1]. The measurement of disability constitutes a complex multidimensional experience and poses several challenges as determining the level of disability since these vary from one country to another, the operational measures in each country and family before a disabled person and the way in which it is conceived socially a disability [2]. Once the measurement obtained may then conduct a comprehensive rehabilitation process.

The upper extremity characterized by its mobility and ability to grasp, hold manipulate and carry out fine motor activities (manipulation) [2]. Unlike the lower extremity, whose functions are support, stability, and locomotion, the upper extremity is highly mobile, allowing it to position the hand in space [3]. The limb is considered as a body chain, driven by the muscles-tendons, which are involved in the general movement and others are responsible for fine movements [4]. The member governs the speed, the range of movement, the forms of grip, and the size of the push-ups. These characteristics are especially relevant in the hand, when carrying out manual activities such as buttoning a shirt, feeding, and writing, among others [5][6]. There is an interaction to coordinate the segments to perform a smooth and efficient movement at the distance or position of the required work. The efficiency lies in the function of the hand, which results largely from the ability to place it in the most appropriate position by movements of the scapulothoracic, glenohumeral, elbow, radioulnar and carpal joints [7].

The human body is subject to present accidents, injuries or diseases (osteoporosis, stroke, aging, etc. [8]) causing the quality of life decay. Cerebrovascular disease is one that affects the blood vessels that supply blood to the brain, it is called Vascular Brain Accident (CVA), embolism or thrombosis [9][10]. Because of this rupture or blockage, part of the brain does not get the blood flow it needs, causing nerve cells in areas of the affected brain not to receive oxygen, so they cannot function and die after a few minutes. Stroke survivors have variable outcomes: some experience spontaneous recovery, while others suffer clinical deterioration [9]. Loss of muscle function after these types of conditions can be serious and often will not return completely, even with treatment [11].

Due to the above, science and technology in many countries have faced the problem of aging societies, to improve their quality of life [12], also many researchers have

The associate editor coordinating the review of this manuscript and approving it for publication was Suélia Fleury (*Corresponding author: Luis Vázquez Sánchez*).

Luis Vázquez-Sánchez, and M. Arias-Montiel are with the Mixteca Technological University, Oaxaca, 69005, Mexico (e-mails: luisvazquezs@mixteco.utm.mx, and mam@mixteco.utm.mx).

M. Adam-Medina, C.D. García-Beltran are with the National Center for Research and Technological Development (e-mails: manuel.am@cenidet.tecnm.mx, and carlos.gb@cenidet.tecnm.mx).

focused their efforts on the social problems generated by strokes, such as abandonment, lack of rehabilitation, a lack of good quality of life, etc., [12][13]. Recently, some assistive devices such as electromechanical assistance, known as robotic exoskeletons, have been developed to help the movements of a person's daily life as one of the solutions to these problems [14][15][16-23][24][25] and there are many others in the line of rehabilitation of the upper extremity for rehabilitation. Although the advance in the development of exoskeletons, it is still far from emulating the movements of the human body. It is due to limitations in the area of hardware design, also in the development of control algorithms for autonomous robotic exoskeletons.

Exoskeletons are external skeletons that are used to support and protect the body of an animal. The robotic exoskeletons belong to the class of mechatronic systems designed to improve the physical capacity of the user, be it a healthy person or a person with physical disability [26]. The history of exoskeletons dates back to 1890, when Nicolás Yang in Imperial Russia patents the first device cataloged as an exoskeleton for walking, jumping and running [27]. In 1917, Leslie C. Kelley patents the Pedomotor, which is assistance in walking, running and improving movements of the wearer, as well as relieving muscles from stress [28]. In recent years, research on the analysis and design of robotic exoskeletons for the upper extremity has increased [29], where they refer to important parameters that must be taken into account and make a classification according to the part that apply, degrees of freedom (DoF), type of application, types of actuators used, use of sensors, control schemes, etc.

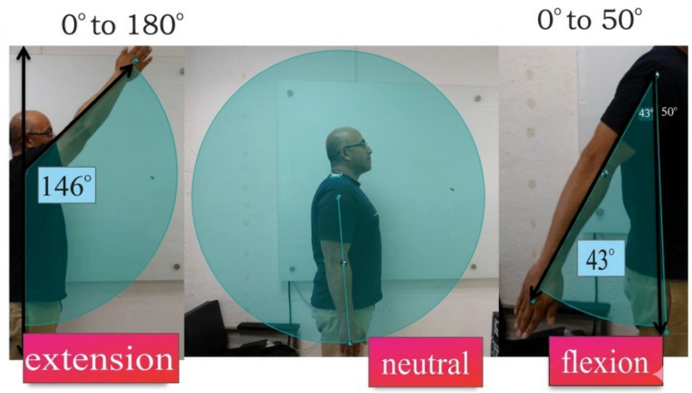
A robotic exoskeleton of upper extremities that uses a law of control based on a mathematical model to support rehabilitation tasks can eliminate the need to use electromyography (EMG) signals and force sensors; you can also use compensation techniques to manipulate robots [30]. The detection of movements of the upper limbs for control purposes for robotic exoskeletons has generated much research, to emulate the limb. It is still far to reach the desired objectives, since the robots have not yet developed to such an extent to emulate 100% movement of the body. This is due to limitations in the area of adequate hardware design and to the control algorithms to develop [31].

The document structured as follows: Section II shows the biomechanics of the upper extremity. Section III shows considerations for the design of a robotic exoskeleton. Section IV control strategies for robotic exoskeleton of upper extremities. Section V shows the robotic exoskeleton classification for upper extremities. Section VI shows the proposed robotic exoskeleton. Finally, section VII presents the conclusions.

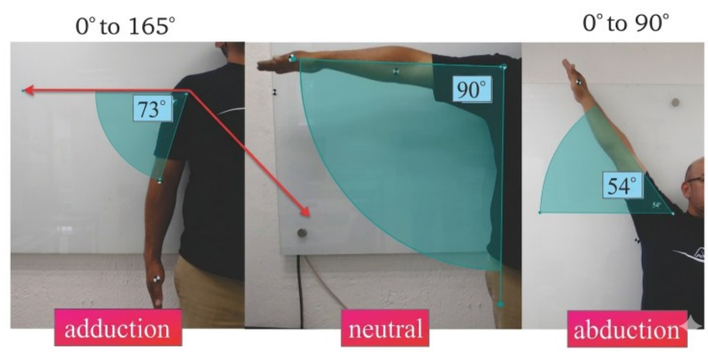
II. BIOMECHANICS OF THE SUPERIOR EXTREMITY

The human motor system is mostly redundant and can have multiple solutions for various actions; the upper extremity is the system that can designate a greater diversity of solutions for various movements [32]. In [33] the identification or recognition of these movements achieved intentionally, using EMG signals. The studies that allow referencing the mathematical models against the biomechanics of the upper limb generate trajectories that will allow to make comparisons with the simulations and, thus, observe which will determine the approximation to the natural movements as presented in [34].

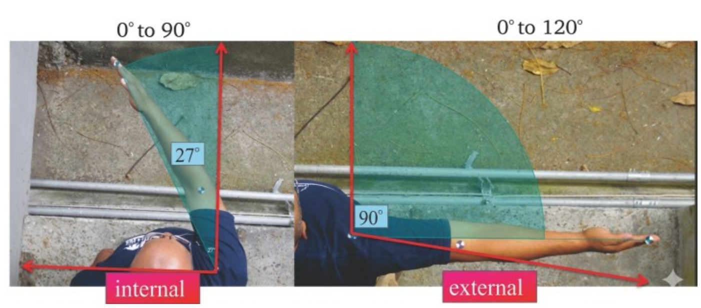
The biomechanics of the shoulder has a great capacity for movement, and it is possible to move in the three spatial planes as shown in Fig. 1; the biomechanics of the forearm observed in Fig. 2 and in Fig. 3, the movements that the carpal joint can perform to observe.



(a)



(b)



(c)

Fig. 1. Shoulder range of movement. a) flexion-extension, b) Abduction-adduction c) Internal-external rotation.

The angles of each joint vary according to the test subjects, due to their anthropometry and physical conditions (build, daily activities, and sports, among other factors). Table I shows the average values of the different joints of the upper limb.

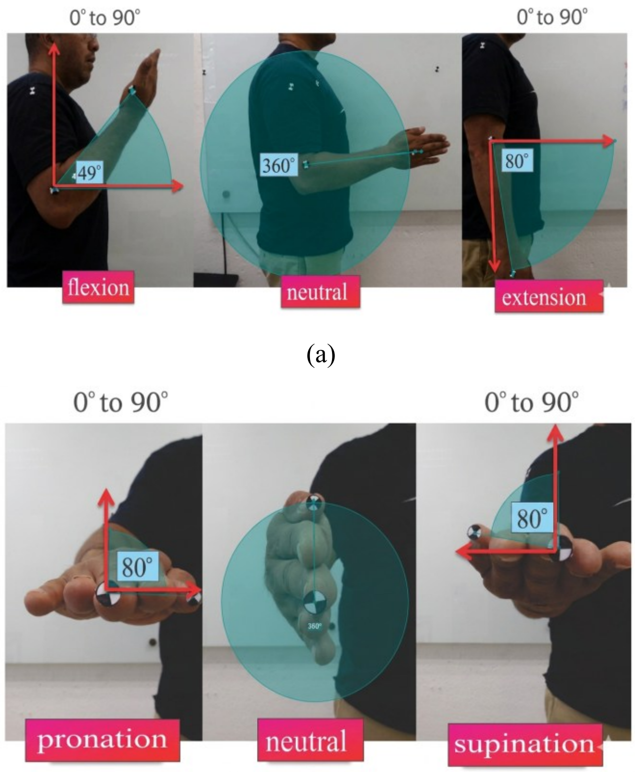


Fig. 2. Forearm range of movement. a) Flexion-extension, b) Supination-pronation.

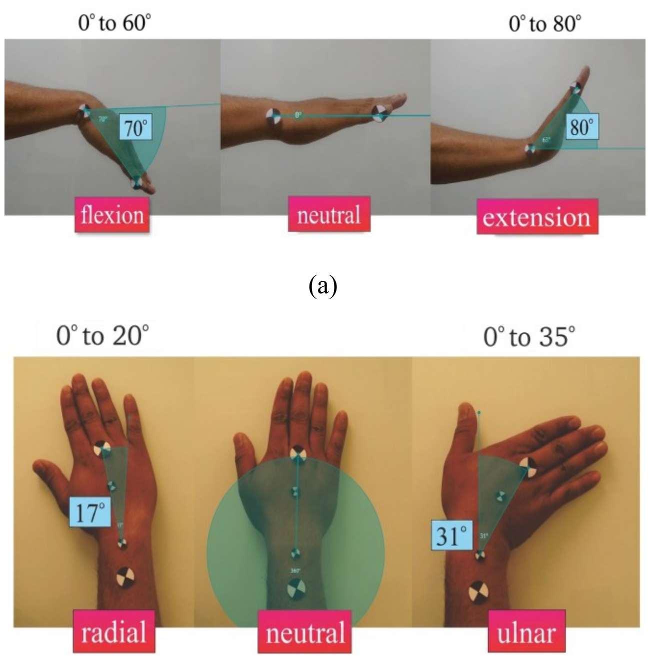


Fig. 3. Wrist range of movement. a) Flexion-extension, b) Radial-ulnar deviation.

TABLE I
RANGE OF MOVEMENT OF SOME OF THE DEGREES OF FREEDOM OF THE UPPER EXTREMITY

joint	movement	angle	movement	angle
shoulder [35], scapulatoraxica joint	extension	180º	flexion	50º
	aduccion	90º	abduccion	70º
	internal rotation	35º	external rotation	140º
	scapula retraction		Scapula protraction	
	circunduction	360º		
forearm and elbow [36], humero-radial-ulnar joint	extension	0º	flexion	135^0
	supination	90º	pronation	90º
Wrist [37], radiocarpal joint, external-internal joint of the distal chamber.	extension	65º	flexion	65^0
	radial deviation	20º	ulnar deviation	30º

III. Considerations for the Design of A Robotic Exoskeleton

In the case of robotic exoskeletons for rehabilitation, researchers assume that a patient will use it only for a certain period of time, ranging from an average of at least three months [38], or if the damage is greater it may be used permanently [26]. Therefore, it should design thinking for a long period.

Has reported that the type of joints required to provide the movements in a natural way complicates the design of an upper limb exoskeleton. In addition, the structure can cause certain discomfort when forces greater than those that the muscle-skin can withstand, or produce pressure that prevents good blood circulation. Therefore, several researchers have dedicated exclusively to the part of the contact between the robotic exoskeleton and the parts of the body that receive external forces. The use of new manufacturing techniques with various materials, such as polycarbonate, and integrating different scientific disciplines can improve the weight of robotic exoskeletons [39].

The characteristics mentioned in [8], such as mass, moment of inertia and the lengths of the different segments are very important since they affect the DoF of rotation. The objective of considering these parameters is to create a light design with the simplest possible mechanisms, thereby minimizing control effort. In addition, the use of new technologies and the development of new materials will help reduce efforts throughout the structure.

Also, it must be adaptable to the lengths of the user's extremities [40]. Synergies in the normal rotation of flexible joints must be replaced by fixed pathological patterns of rotation, so that it is able to change the joint synchronization of performance exercises in rehabilitation [32]. Anatomical joints can be modeled in the workspace as [41]: a spherical joint for the glenohumeral joint, a pivotal joint for the cubital-humerus, a cylindrical joint for the radio-ulnar joint, and a universal joint for the carpus Fig. 4.

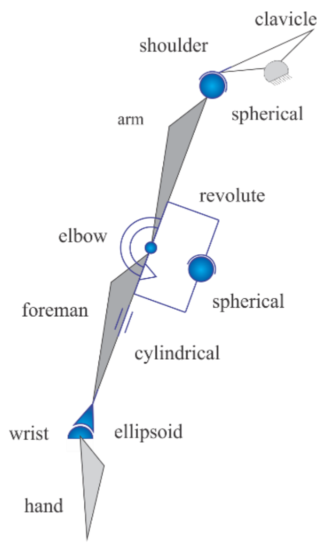


Fig. 4. Joints and bones of the upper extremity and its model.

The mHMIs (Mechanical Human-Machine Interfaces) are mechanisms that connect the human arm to the structure of the exoskeleton, and allow the transmission of forces between both [42]. If the robotic exoskeleton is a kinematic replica of the user's arm and is next to it, it is required to transmit forces from the robotic exoskeleton to the arm. The contacts of the mMHIs are placed in the most appropriate position to emulate movement dynamics, improve the efficiency in the contact and movement of the scapulothoracic, glenohumeral, elbow, radioulnar and carpal joints [43], [44]. Figure 5 presents various mMHIs designed and implemented for distinct functional applications in the orthosis system. In addition, the comprehensive study of the biomechanics of the upper limb is still under study.

a) b) c)

Fig. 5. Different forms of mMHIs, for different contacts. a) bionic leg orthosis, b) Orthotic Sling, c) ESA - X-Arm-II exoskeleton

This robotic exoskeleton for the forearm and wrist designed to operate in two modes: passive and active. In the passive mode, a controller drives the joints along pre-defined trajectories, moving the user's limb for rehabilitation purposes. In the active mode, the system detects the user's motion intention via Electromyogram (EMG) signals. By utilizing these signals to inform a dynamic model of the upper limb segments, the controller can estimate the required torque in real-time. This allows the exoskeleton to predict the intended routine and provide precise assistive force, dynamically adapting to the user's physiological input rather than relying on a fixed geometry [45],[46]. Furthermore, the extraction of accurate kinematic parameters from volumetric sequences serves as a direct link between human motion intention and robot behavior, allowing for non-invasive and natural control interfaces. [47].

Furthermore, developing a kinematic model constitutes a critical design phase to validate the mechanism's workspace. This ensures the exoskeleton can replicate the physiological range of motion required for Activities of Daily Living (ADL) while avoiding kinematic singularities [41]. The volume within which all points reached by a chosen reference point on the wrist called an accessible workspace. Various forms exist to obtain the kinematic models of the limb, in [48] it uses a sequence of data captured by real-world cameras and, a volume of synthetically generated data from a 3D geometry articulated with an arbitrary kinematics. Which generates underlying non-linear axes or skeleton curve of a volume and describe the curves in a kinematic model and the movement in a volume sequence. For its part in [49] performs a data collection using a VICON motion capture system at a frequency of 120 Hz, which allows to characterize the kinematic model. The work of analysis of the kinematics and dynamics of the upper limb, reported in the literature, show patterns with respect to the standard DoF, described by the joints. These patterns used to perform the analysis for different robotic exoskeletons, according to the required requirement [8],[13],[31],[35],[37],[45],[50].

Characterizing the signals that used as a reference is important, since when determining an input signal, the type of components that used to filter the signals correctly known. It is also known if it will be passive or active [50], what type of material analysis should be performed, actuators to be used, sensors, how many DoF, injury data, treatment data to injuries, etc. [31]. Taking into account what in [44] describes as input signals, Fig. 6 shows a classification made of the types of input signals commonly used in the robotic exoskeleton of upper extremities. The muscles of the upper limbs that are involved in movement taken into account as variables in the time of a signal in a mathematical model. For the characterization or identification of the system, as it may be non-linear, as well as an input signal would not be stationary with respect to time, and muscle fatigue should be included in modeling [51].

Therefore, it has to be designed as an orthotic device biomechanically integrated with the upper limb, as also in [20] it defines it as the exoskeleton-type rehabilitation robot has a more complicated mechanical structure that mimics the skeleton of the human body and ensures the alignment of the axis of the joint of the robot and the corresponding human.

IV. Control Strategies For Expert Extremities Superior

The use of technologies in robotic rehabilitation exoskeletons for control is important to improve the effectiveness of clinical treatment [20]. Since there are no two identical lesions, the challenge of developing a robotic rehabilitation system that can be adapted to each case is quite high [52]. Control strategies are developed to repetitively guide the extremities of patients in anatomically and ergonomically viable trajectories so that patients can regain muscle strength [53]. The development of these control strategies has also been an important area of research in the rehabilitation of the upper limb of the robot. Control strategies can be used for different applications in each design [42][54], which can be: i) Physiotherapy, ii) assistance (human amplifier), iii) haptic and iv) teacher/slave.

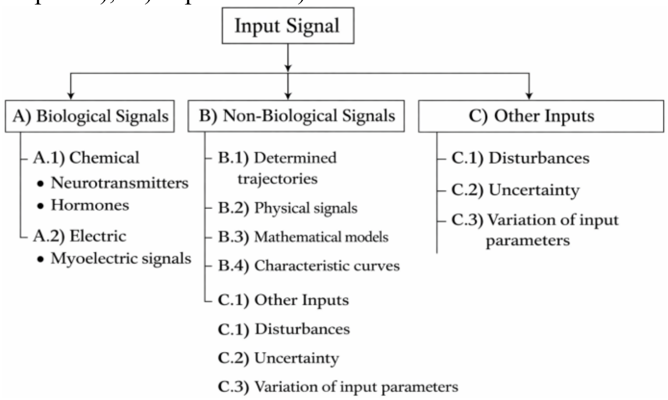


Fig. 6. Classification of input signals of a robotic exoskeleton in a general way.

Predicting the movements by means of biological signals, in real time, to use in the laws of control to assist a robotic exoskeleton, allows the movements to be more natural and not to frustrate the patient for any delay in acting. However, transforming EMGs into frequency domains for manipulation usually results in signal losses, by the quality of the sensors or mathematical models, and constitute a delay in real-time control [55]. In [19] the use of kinesthetic feedback for rehabilitation purposes proposed, which allows a control in the coordinated physical activities, and thus the system obtains a significant learning to apply it to the neuro-rehabilitation. In [56], they based on functional electrical stimulation (FES) or on rehabilitation robots and haptic interfaces. It is a technology that uses small electrical impulses to artificially activate the peripheral nerves, causing the muscles to contract, and this is done to restore the functions of the body, this development is a Haptic Smart Robot Glove (IHRG), for the rehabilitation of patients who have a diagnosis of a stroke.

Others make comparisons between the laws of control, to demonstrate the strength and effectiveness of a proposed algorithm to stabilize the system against parametric uncertainties, paired and mismatched perturbations, as is the case in [57] with adaptive sliding mode. With Fuzzy PID in [17], the response speed with second order sliding mode [15] is further improved. Also in the ETS-Motion Robots [58] it is robust to react to unforeseen external forces and does not require precise knowledge of the dynamic parameters. Using robustness analysis will also allow controlling parametric uncertainties such as sensory noise or environmental contacts [59], etc.

Currently with the existence of various automatic learning techniques and advanced algorithms in signal processing, the machine-brain interface has improved in recent times. It is important to take into account the control that will be used, since it will allow knowing what are the types of sensors and actuators suitable; and remembering the important part that has been mentioned that there is no equal injury. Considering what done in [44] and increasing the data, in Fig. 7 various control laws are shown.

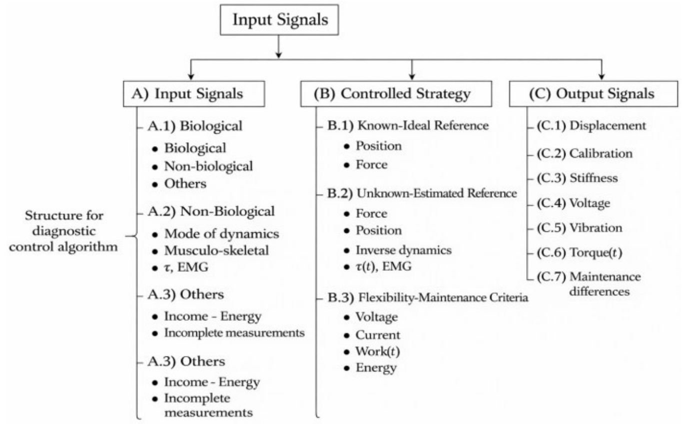


Fig. 7. Classification of some control methodologies for robotic exoskeleton of superior members.

V. Classification of Exoskeleton Robotic for Upper Limb

Research for the development of devices for rehabilitation is currently divided into four types of applications, which are conceptually different [22, 33, 34] Fig. 8.

Relevant developments in upper-limb robotics were identified through a review of databases including IEEE Xplore, ScienceDirect, PubMed, and Google Scholar. The search wasn't limited, timeframe to focus on state-of-the-art technologies, utilizing search strings that combined terms like: Upper-limb exoskeleton, Stroke rehabilitation, and Mechanical design. The screening process selected studies describing functional prototypes (shoulder, elbow, wrist) with detailed DoF and control specifications. Articles were excluded if they focused on lower limbs, prosthetics, or lacked experimental validation, ensuring the review centered on viable rehabilitation solutions.

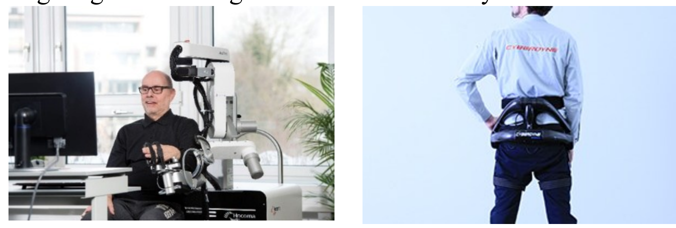
Physiotherapy Device. The exoskeleton supports functional activities of daily living and structured rehabilitation in active or passive modes, adapting to patient motor capacity. The Armeo®Spring enables independent training of the shoulder, arm, and hand within a three-dimensional workspace and includes quantitative assessment tools to monitor progress. However, access to such advanced rehabilitation technologies remains limited in many regions. [101].

Assistive device (human amplifier): HAL by reading the bioelectric signals, the device assists wearer's movement according to his/her intention and reduces stress applied on the lumbar region when he/she lifts or carries things. The light weight of 3kg and compact design of this device allow the wearer including woman and/or aged one to work for longer hours without fatigue.

Haptic device: the subject interacts with virtual objects while the forces generated through the feedback interaction of the user through the exoskeleton as a form of transport, textures or other characteristics of virtual objects. The CyberGrasp system is an innovative force feedback system for your fingers and hand. It lets you "reach into your computer" and grasp computer-generated or tele-manipulated objects. The CyberGrasp device is a lightweight, force-reflecting exoskeleton that fits over a CyberGlove data glove (wired version) and adds resistive force feedback to each finger. With the CyberGrasp force feedback system, users are able to feel the size and shape of computer generated 3D objects in a simulated virtual world (cyberglovesystems.com).

Master device: replacing the virtual environment with real control, the operator uses the control to control a robotic system in an operation mode (master / slave). The MyoPro Motion G is the next generation of the MyoPro myelectric upper extremity orthoses and combines myoelectrically driven 3-jaw chuck grasp with the functionality of the MyoPro Motion W. It designed to increase functional capability for the user by enabling partial finger movement and resulting hand control. The MyoPro Motion G orthosis empowers a user to complete additional functional tasks by enabling grasping of objects along with elbow flexion and extension. The device promotes a higher level of independence through increased functional activity and safety that may result with the increased capability of an affected arm (myomo.com).

In recent years, research efforts have significantly increased in the analysis and design of robotic exoskeletons targeting different regions of the human body.



a) b)

Fig. 8. Two examples of R_EXO classification for rehabilitation: (a) Physiotherapy: Armeo®Spring. (b) Assistance: HAL®.

Several studies have focused specifically on upper-limb exoskeletons, as reported in [18], [26], [38], [45], [53], and [60]. These works examine a variety of design and performance characteristics, including degrees of freedom, supported movement patterns, mechanical development, control strategies, portability, total weight, and clinical validation. Such comparative analyses contribute to the systematic evaluation and advancement of upper-limb robotic exoskeleton technologies. Table II shows a classification of robotic exoskeletons for upper extremities, to complement information from previous authors.

TABLE II
A COMPARISON OF THE MAIN CHARACTERISTICS OF UPPER-LIMB EXOSKELETONS

Reference and dates	DoF	Actuator	Purpose and Movement Mode	Sensor	Movements	Control, comment	Portabl e	Weig ht (kg)
M.Babaisal, Ghanbari, Noorani 2013 [8]	**3**	Mechanical design, simulation and control	Rehab for VBA (passive)	n/d	S: F-E, AB-AD, I-E	Reverse Dynamics: track desired trajectory. The proposed controller can efficiently reject the disturbance and other uncertainties	n	11.4
Zhang, Yang, Wang, 2018 [15]	5	Design	Simulation	n/d	S: AB-AD, F-E; E F-E F: P-S	Multivariable Finite-Time Control, sliding modes, Linear extended observers	n/d	n/d
Kühn, Hu, Schamppler, 2018 [16]	6	Simulatión	Assistance	n/d	S: AB-AD, F-E; E: F-E F: P-S, W: R-U, F-E	Gravity compensation and kinematic latent-space impedance control	n/d	n/d
Onozuka, Suzuki, Yamada, 2018 [22]	4	Clutches of magnetorheol ogical fluid and artificial muscles	Assistance (elastic force)	Head mounted displays, weight compensati on mechanism	S: AB-AD, F-E, I-E E: F-E F: P-S,	Closed loop force device	No	20
Yin-Yu, Ching-Hui, Ying, 2018 [23]	5	Motor step PKP225 226Nm	Rehab (fine motion)	Elastic series SEA for force and impedance, optical encoder Renishaw atom	E: F-E F: P-S, W: R-U, F-E	n/d	Yes	3.5
Ugurlu, Barkan Nishimura, Masayoshi Hyodo, Kazuyuki, 2015, [30] TTI-Exo	6	Harmonic Drive FHA-14C-Mini series of brushless servo motors are	Aided therapy (active)	EMG sensor with noninvasive electrodes.	S: F-E, I-E, E: F-E	Disturbance Observers with EMG	y	n/d

Rahman, Saad, Kenné 2010 [31]	2	Motor cd Maxon-EC45	Rehab Modeling, (passive)	Pressure sensor	F: P-S E: F-E	Non-linear sliding modes	n	n/d
Kiguchi, Hayashi, 2004 [35]	7	DC motor	Rehab Assistance (active)	16 Input EMG electrodes, to estimate movements	F: P-S E: F-E W: F-E, R-U S: AB-AD, I-E	Neuro-diffuse modifier structure that is equal to a neural network and the process of signal flow is fuzzy reasoning.	n	n/d
Xiao, Elnady, Menon, 2014 [36]	1	DC motor	Modeling (active intension)	FSR belts	F: P-S	EMG, position detection ,	n/d	n/d
Pehlivan, Lee, O´malley, 2012 [37], **RiceWrist**	3	DC Motor brushless	Rehab for VBA or spinal damage (passive)	Touch sensors	F: P-S W: F-E, R-U	kinematic analysis	n/d	n/d
Pehlivan, Chad, O'malley, 2013 [50]	3	Applimotion 165-A-18, Maxon RE-40 (148877), Maxon RE-30 (310009) Transmission	Rehab (passive)	MicroE Mercury 1500 Avago HEDS 5540 Avago HEDS 5540	F: P-S W: R-U, F-E	PD	No	n/d
Brahim, Saad, Rahma, 2018 [58] ETS-MARSE	7	Motor Maxon EC-45, EC-90,	Motion Assistive	sensores de fuerza NANO17-R-1.8-M2-M1PCI, NI PXI-7813R;	S: AB-AD, F-E, P-S, I-E E: F-E W: R-U , F-E	Adaptive control, the design of a tracking control that can estimate the uncertainties and unexpected disturbances and decrease its effects to achieve the desired tracking performance	No	10
Gupta, O'Malley, Patoglu 2008, PUMA-560 [61]	4	Maxon Motors, #RE40, brushless DC motor Ap-plimotion Inc., # 165-A-18	Rehab and Training	pneumatic breakaway overload sensor set to 20 Nm, quick-release coupling mechanism	F: P-S W: R-U, F-E	PD, Task-space impedance	n/d	1.96
Jung, Bae, 2014 [62]	5	n/d	Educational	Force sensors (ATI, mini45), potentiomet ers, conical drive gears	S; F-E, C. AB-AD E: F-E, P-S	Linear trajectories	n/d	n/D
Kinematic, IEEE, 2012 [63]	3	Megaflux frameless torque motors, hydraulic, pneumatic	Rehab, motor assistance, military use	n/d	S: F-E, I-E , E: F-E	Rehab, motor assistance, military use Based on forces and movement intension. It has numerous potential applications in industry, emergency services and the military.	n	n/d
Hong,Kim,K. Kim 2012 [64]	10	Simulation	Power assistant system	n/d	W: P-S, R-U, F-E	Not specified	Yes	n/d
Rahman, Saad, Kenné, 2011 [65], MARSE-4	4	Brushless DC motor, complex cable transmission	Rehab therapy (passive)	Pressure sensor	F: P-S E: F-E W: R-U, F-E	PID, employed to follow pre-programmed trajectories that correspond to passive Rehab exercises	No	n/d
Zhang, Quo, Ku 2014 [66] Phantom Premium	2	DC Motor, pulleys, high ratio reducers (231: 1)	Neuro-Rehab (passive), partial assistance	Force sensor FS03 Honeywell, EMG electrodes, MTx inertia sensors, Xsens Tech	Forearm: P-S Elbow: F-E	High and low impedance control	No	1.3
Wei, Gou, Zang 2013 [67] PHANTOM Premium 1.5	2	Motor, pulleys	Neuro-Rehab (passive)	Force sensor FS03 Honeywell, EMG electrodes, MTx inertia sensors,	F: P-S E: F-E	Virtual reality	No	1.3

				Xsens Tech				
Song, Guo, Pang 2012 [68] ULERD	7	Maxon BLDC motor, gearhead reducers, cables	Rehabilitación (passive)	MTx inertial sensor, electrodes for EMG dry, encoder	F: P-S E: F-E W: F-E	Impedance control, measures the motion input by the user and the user returned force. Admittance control, measures the forces exerted by the user and the device to react with the appropriate offset.	Yes	s/d
Kimura, Genda, Nakamura 2014 [69] Portable Spring Balancer	4	DC motor, one spring	Assist device for high cervical spinal cord injury. (active/passive)	acceleration sensor and switches	W: 3D F: P-S	PID control, desired trajectory position control; residual function such as head motion or shoulder motion by the trapezius muscle	No	n/d
Kang, Wang., Yu 2013 [70]	5	n/d	Rehab (passive)	n/d	F: P-S E: F-E W: F-E, R-U	Adaptative observer based controller, the proposed controller can guaranteee the robustness of the robotic system en the presence of model uncertainties	No	n/d
Kim, Park, Gi 2017 [71] NCCEES	1	Maxon EC90 Flat motor 4.94 Nm	Rehab (passive)	The EMG acquisition system WEWG	Elbow: F-E	EMG based on variable impedance	No	1.5
Brielle, Williams, Ben-Tzvi, 2018, SAFER [72]	1	1:1000 high power miniature gearmotors with long-life carbon brushes (HPCB).	Rehab and Assistive Applications	FSR (force-sensitive resistors)	W:F-E	Hysteresis controller	y	n/d
Abooee, Arefi, Sedghi, 2018 [73]	5	AC and DC servo motors	Rehab	n/d	S: AB-AD, F-E, I-E E: F-E W: R-U, F-E	the nonsingular terminal sliding	n	n/d
Crocher, Fong, Bosch, 2018 [74]	4	n/d	Neurological Rehab	Magnetic sensors trakSTAR	S: AB-AD, F-E, I-E	3D gravitational compensation	n	n/d
Zheng, Jinyu Shi, Ping Yu, Hongliu, 2018 [75]		Visual Studio platform	Virtual Reality Rehab (active/passive)					
Pei S Wang J Guo J, 2023 [76]	7	DC servo motors	Rehab	Torque sensor	S-E-F	gradient-based inverse kinematics algorithm	n	n/d
Abdallah I Bouteraa Y, 2024 [77]	2	Geared Servomotor	Rehab	AgCl electrodes	E-F	Fuzzy Logic-Based Pain Detection	y	n/d
Li H., Gou S., Wang H., 2023 [78]	2	Brushless motor EC2240 maxon	Rehab	UDP LAN Force sensor	S- A-F	ESCON velocity control	y	1.35
Ni P, Sun J, Dong J., 2024 [79]	3	DC servo motor	Rehab	Force sensor	E-F-W	Impedance control scheme of PSO-BP neural	n	n/d
Meng Q, et.al., 2019 [80]	6	Dc motor, harmonic reducer	Rehab	n/d	S-E-	Simulation	n	n/d
Burns M, Zavoda Z, et.al. 2020 [81]	3	Pneumatic	Stoke Rehab	Transducer pneumatic, Nitra AVS-53 5/3 solenoid valves	S- E	Arduino Mega2560x microcontroller, It does not indicate the Control Law	n	n/d
Rangan P, Johnson J, et.al. 2023 [82]	5	n/d	n/d	n/d	S-E-W	Design and Modelling	n	n/d
Hu S, Zhou X, Bao, J, 2023	n/d	Model schematic	n/d	n/d	Upper limb	Parameter optimization	n/d	n/d

[83]								
Gou J, Li P, 2020 [84]	5	Model Schematic	Arm rehab	n/d	S-E-W	Kinematic and dynamic simulation of the robot	y	1.8
Nuñez J, et al. 2020 [85]	3	Model Schematic	motor and neuromuscular rehab	n/d	S-E	PD controller and a PID controller	n/d	n/d
Chiaradia D, Rinaldi, G, et. al. 2024 [86]	5	DC motor through tendon transmission	Rehab-Exos	contact forces/torques	S-E-W	dynamic compensation. Inertial and Coriolis effects, passivity		3.7
Ito D, Fukuda M, et.al. 2024 [87]	4	n/d	Rehab-clinical study	n/d	S-E	Surface electromyography (EMG) recording device and an electrical stimulator into the robot's real-time control system	n	n/d
Ahmed T, Islam R, et.al. 2022 [88]	7	Brushless DC motors Maxon EC 90	Rehab-exo robot	Force/torque sensor	S-E-F-W	Classical PID controller's stability	n	n/d
S. Pei, J. Wang, J. Gou, et.al. 2023 [89]	7	DC motor	Rehab-exo	Force/torque sensor	S-E-F	Controller was designed based on the industrial PC CX6015-0100	n	n/d
T.M. Kwok, T. Li. And H. Yu, 2023 [90]	3	n/d	VR therapy	IMU-ArUco sensor	Pro/ret scapula	virtual ADL	n	n/d
H. Morishita, T Murakami, 2023 [91]	2	motor	assistance	EMG	S-E-F-W	Control of physical HumanRobot Interaction	y	n/d
M.H. Yen, L. H. Yao, 2023 [92]	2	Motor dc	rehabilitation training	EMG	F-E S	surface electromyography	n/d	n/d
M. Abdallah, R. Fareh, Y. Kali 2024 [93]	7	Motor cd	Rehab-exo	Simulation	S-E-F-W	PID	n	

VI. PROPOSAL ROBOTIC EXOSKELETON

The following key factors underscore the significance of the proposed upper-limb exoskeleton design, as identified through the background research.

1. Addressing the Rehabilitation Gap: The design responds to the critical shortage of therapeutic coverage for stroke survivors, offering an automated alternative to labor-intensive manual therapies.

2. Cost-Effectiveness and Accessibility: Unlike high-end commercial systems, this proposal focuses on a low-cost, portable architecture to enhance accessibility for underserved patient populations. 3. Restoration of Functional Autonomy: The system targets the upper extremity's complex range of motion to restore independence in ADL, moving beyond simple repetitive movements. 4. Kinematic and Biomechanical Compliance: The proposed 5-DoF mechanism is designed to maintain precise alignment with human joint centers, mitigating the risk of injury caused by non-physiological movements. 6. Ergonomics and Material Selection: The integration of lightweight materials (POM and aluminum) and adjustable anthropometric parameters ensures a wearable design that reduces metabolic cost and improves patient comfort during extended rehabilitation sessions.

For the movement ranges, the literature was used to collect the data of the angles and lengths reached by a healthy patient [76][77]. The analysis of these data allows obtaining information to verify the requirements that are required when designing the robotic exoskeleton and other relevant technical data that required studied or analyzed. To measure the ranges of motion in the sagittal plane and frontal plane in a healthy subject, a Sony 56 digital camera and a Cannon camera used and, due to its reliability to measure the range of motion, the Kinovea® 0.8 application used. [26] [78]; it is a free software that allows us to perform kinematic analysis, comparison and evaluation of sports and training [79]. You can also explore and comment on the biomechanical actions, this tool allows modifying and managing by video or photography in a simple way the kinematic measurements.

The knowledge of the anthropometric parameters of the human body is essential to understand human kinematics, and particularly for design [52]. Considering viable information of size, weight and center of mass in the body, moments of inertia, orientation and the shape of each segment. For the design of the NITA-01 robotic exoskeleton, the musculoskeletal data taken into account regarding weight, joints, work angles, lengths, torque and volume in the segments where the mIMHIs placed. In Table III, you can read which some anthropometric values that used in the design were. Similarly, in Table IV, the inertial properties of the related segments read for the design of the robotic exoskeleton such as arm, forearm and hand. The properties are of an adult person.

Taking into account what was investigated, a proposal is made of a robotic exoskeleton for rehabilitation that is shown in Fig. 9 of 5 DoF for shoulder: flexion/extension, adduction/abduction; elbow: flexion/extension; carpus: flexion/extension, radial/ulnar deflection. Which focused on the rehabilitation of people who have survived a stroke, and who require ongoing therapy. The NITA 01 robotic exoskeleton designed to be portable, lightweight, and inexpensive.

TABLE III
PERCENTAGES OF DIFFERENT BODY PARTS ACCORDING TO THE MASS AND SEX. MOVEMENT RANGES OF SOME OF THE DEGREES OF FREEDOM OF THE ABOVE **[95]** END. MAXIMUM TORQUE CAN EXERCISE THE UPPER LIMB FOR EACH OF ITS MAIN DEGREES OF FREEDOM [80]

weight (kg) [76] [77]		**articulation, movement**	**work angle [81]**	**torque**
hand	0.7	wrist: flexion-extension	75-65	19.8 Nm
forearm with the hand	3.0	radial-ulnar	30-20	20.8 Nm
elbow	2.6	Flexion-extension	135-0	72.5 Nm
forearm without the hand	2.3	Shoulder: flexion-extension	180-50	110 Nm
Complete arm	5.6	Abduction-adduction	48-134	125 Nm

TABLE IV
INERTIAL PROPERTIES OF SOME BODY SEGMENTS

Segment	**Distance gravity center (GC)**		**Location turning radius when the segment rotates about**		
	proximal	**distal**	**GC**	**proximal**	**distal**
hand	50.6	49.4	29.7	58.7	57.7
forearm	43.0	57.0	30.3	52.6	64.7
arm	43.6	56.4	32.2	54.2	64.5

The system mounted on a polyoxymethylene (POM) plate. Abduction-adduction is performed by the motor 1 that transmits the force by means of cables to the pulley 1; and is transmitted to the movement to the axis 1, which is the element that makes the greatest effort and that is why it is designed in aluminum and is in the form of L. The engine 2 performs the flexion-extension of the shoulder and the pulley attached to the shaft 1 to be able to combine movement simultaneously. The motor 3 performs the flexion-extension of the elbow in combination with the pulley 3, for the flexion-extension of the carpus the motor 3 is used to move the mechanism making the effort for the movement, and for the radial-ulnar deflection together with the motor 5 is a mechanism that has an integrated worm and a flexible cable. Although most exoskeletons use gear mechanisms, here is the proposal to use wires and flexible cables, to lighten the weight of the exoskeleton.

Many of the components the idea is that they are in 3D printing, but now the material that is available as aluminum and polyoxymethylene used.

VII. CONCLUSIONS

The design and development process of a robotic exoskeleton is complex due to the various components involved, such as the shoulder mechanism, elbow, forearm, wrist, embedded system, battery, and the parameters required to establish a control strategy. It is important to consider the uncertainty of biological parameters that describe the functional and individual characteristics of each person. These uncertainties mainly arise when the desired movements are attempted, but the proposed angles cannot be fully achieved. To complete them, additional movements are required.

A clear example is shoulder abduction: during a typical movement, it may reach 165°, but to achieve 180°, an additional combination of degrees of freedom is needed, such as pronation, horizontal flexion, or retroposition. These uncertainties are taken into account in the design of the exoskeleton to limit such movements according to the planned degrees of freedom.

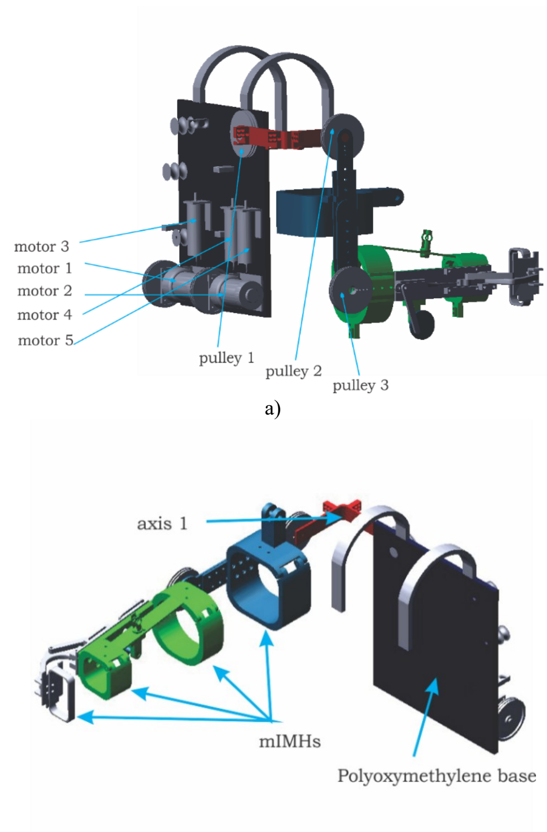


Fig. 9. NITA-01 five-DoF exoskeleton, under development at CENIDET. a) Isometric view of the exoskeleton showing the mechanisms. b) Isometric view of the exoskeleton showing the basic instrumentation.

The main contributions of this work are the presented data. First, a recent review of robotic exoskeletons is carried out to improve classification in terms of upper extremities based on various design characteristics and to identify similarities among different models currently under research and development in various locations. Relevant aspects such as control models and the variables considered are highlighted. Additionally, a compilation of the most commonly used control strategies is provided, identifying those that are optimal for the performed tests, along with key components for automation, including sensors, actuators, and more.

This work presented the design and kinematic analysis of the NITA 01 robotic exoskeleton, developed specifically for upper limb rehabilitation in stroke survivors. Unlike current commercial devices, the widespread implementation of which is often hindered by prohibitive costs and limited portability, the proposed 5-degree-of-freedom (DoF) architecture offers a viable solution that balances biomechanical complexity with economic accessibility.

The kinematic analysis results validate that the mechanism is capable of replicating the physiological ranges of motion (ROM) required for the execution of ADL, ensuring precise alignment with the shoulder, elbow, and wrist joints. Furthermore, the selection of lightweight engineering materials, such as Polyoxymethylene (POM) and aluminum, proved effective in reducing the device's inertia—a critical factor for minimizing user fatigue and enhancing ergonomics during prolonged therapy sessions.

Ultimately, this design not only meets technical safety and functionality requirements but also addresses an urgent societal need: democratizing access to neurorehabilitation. The development of the NITA 01 lays the groundwork for future physical prototyping and clinical trials, positioning the system as a key technological tool to decentralize therapy and improve the quality of life for a rapidly growing patient population.

References

[1] United Nations Department of Economic & Social Affairs, Social Inclusion Demographic Yearbook. 2023

[2] K. L. Moore, A. F. Dailey, and A. M. R. Agur, "Human Anatomy with Clinical Guidance", 7th ed. W. Kluwer, ISBN:9788415684770, 2015.

[3] R. L. Drake, W. Vogl, and A. W. M. Mitchell, Gray - "Anatomy for Students", 3th ed. ESP: ISBN: 0-443-06612-4, 2005.

[4] T. T. Choudhury, M. M. Rahman, A. Khorshidtalab, and M. R. Khan, "Modeling of Human Arm Movement: A Study on Daily Movement," *2013 Fifth Int. Conf. on Comp. Intelligence, Mod. and Sim.*, Seoul, KOR, pp. 63-68, Sep 2013, doi: 10.1109/CIMSIM.2013.19

[5] INEGI, People with Disabilities in Mexico, a Vision for 2010, MEX, 2010, ISBN: 978-607-739-055-8.

[6] INEGI, "Group 2 Motor Disabilities," Disability Type Classification, pp. 1–55, MEX, 2010, ISBN: 978-607-739-055-8.

[7] R. A. R. C. Gopura and K. Kiguchi, "Mechanical Designs of Active Upper-Limb Exoskeleton Robots," IEEE 11th Int. Conf. on Rehab. Robot., pp. 178-187, Kyoto, JPN, 2009, doi: 10.1109/ICORR.2009.5209630

[8] M. Babaiasl, A. Ghanbari, and S. M. R. Noorani, "Mechanical design, simulation and nonlinear control of a new exoskeleton robot for use in upper-limb rehabilitation after stroke," 20th Iran. Conf. Biomed. Eng., pp.18-20, Tehran, IRN, 2013, doi: 10.1109/ICORR.2009.5209519.

[9] I. Healthcare, "Stroke treatment", pp. 1-2 doi: 10.1001/archneur.61.7. 1066.Ischemic, USA, 2004.

[10] J. Masjuan, J. Alvarez Sabín,j. Arenillas, et al., "Stroke health care plan" (ICTUS II. 2011), *Neurología*, pp 1-17, ESP, 2011, doi: 10.1016/j.nrleng.2010.05.001.

[11] Secretaria de Salud, "National Rehabilitation Institute", MEX, 2013.

[12] T. D. Lalitharatne, Y. Hayashi, K. Teramoto, and K. Kiguchi, "A study on effects of muscle fatigue on EMG-based control for human upper-limb power-assist," IEEE 6th Int. Conf. Inf. Autom. Sustain., pp. 124-128, Beijing, CHN, 2012, doi: 10.1109/ICIAFS.2012.6419892.

[13] D. S. Andreasen, S. K. Allen, and S. H. Sprigle, "Exoskeleton for forearm pronation and supination rehabilitation," 26th Ann. Inter. Conf. of the IEEE, pp. 2714-2717, 2004, doi: 10.1109/IEMBS.2004.1403778.

[14] H. Yu, I. S. Choi, K. L. Han, J. Y. Choi, G. Chung, and J. Suh, "Development of a upper-limb exoskeleton robot for refractory construction," Ctrl. Eng. Pract., vol. 72, pp. 104-113, March 2018, doi: 10.1016/j.conengprac.2017.09.003.

[1] G. Zhang, P. Yang, J. Wang, and J. Sun, "Multivariable Finite-Time Control of 5 DoF Upper-Limb Exoskeleton Based on Linear Extended Observer," *IEEE Access*, 6, pp. 43213-43221, 2018, doi: 10.1109/ACCESS.2018.2863384

[15] J. Kuhn, T. Hu, M. Schappler, and S. Haddadin, "Dynamics simulation for an upper-limb human-exoskeleton assistance system in a latent-space controlled tool manipulation task," *IEEE Int. Conf. Simulation, Model. Prog. Auton. Robot,* pp.158-165, Brisbane, AUS, Jul. 2018, doi: 10.1109/SIMPAR.2018.8376286.

[16] A. Ali, S. F. Ahmed, K. A. Kadir, M. K. Joyo, and S. R. N. Yarooq, "Fuzzy PID Controller for Upper Limb Rehabilitation Robotic System," *IEEE Int. Conf. Innov. Res. Dev*., pp.1-5, Jun 2018, doi: 10.1109/ICIRD.2018.8376291.

[17] N. Rehmat, J. Zuo, W. Meng, Q. Liu, S. Q. Xie, and H. Liang, "Upper limb rehabilitation using robotic exoskeleton systems: a systematic review", *Int. J. Intell. Robot. Appl.*, vol. 2, no. 3, pp. 283–295, 2018, doi: 10.1007/s41315-018-0064-8.

[18] D. Buongiorno, E. Sotgiu, D. Leonardis, S. Marcheschi, M. Solazzi, and A. Frisoli, "WRES: A Novel 3 DoF WRist ExoSkeleton With Tendon-Driven Differential Transmission for Neuro-Rehabilitation and Teleoperation," *IEEE Robot. Autom. Lett.,* vol.3, no. 3, pp. 2152-2159, 2018, doi:10.1109/LRA.2018.2810943

[19] Q. Wu, X. Wang, B. Chen, and H. Wu, "Development of an RBFN-based neural-fuzzy adaptive control strategy for an upper limb rehabilitation exoskeleton," *Mechatronics*, vol. 53, no. 1, pp. 85-94, 2018, doi: 10.1016/j.mechatronics.2018.06.002.

[20] Y. Ogiri, Y. Yamanoi, W. Nishino, R. Kato, T. Takagi, and H. Yokoi, "Development of an upper limb neuroprosthesis to voluntarily control elbow and hand," *Adv. Robot*., vol.32, no.16, pp. 298-303 2018, doi:10.1109/ROMAN.2017.8172317

[21] Y. Onozuka, R. Suzuki, Y. Yamada, and T. Nakamura, "An Exoskeleton Type 4-DoF Force Feedback Device Using Magnetorheological Fluid Clutches and Artificial Muscles," *IEEE/ASME Int. Conf. Adv. Intell. Mechatronics,* pp. 869-874, 2018, doi: 10.1109/AIM.2018.8452696.

[22] Y. Su, K. Wu, C. Lin, Y. Yu, and C. Lan, "Design of a Lightweight Forearm Exoskeleton for Fine-Motion Rehabilitation," *Int. Conf. Adv. Intell. Mechatronics,* pp. 438-443, 2018, doi: 10.1109/AIM.2018.8452243.

[23] L. Min, W. Guo, G. X. Member, Y. Jia, J. X. Member, and X. Z. Member, "A Tendon-driven Upper-limb Rehabilitation Robot," 15th Int. Conf. Ubiquitous Robot., pp. 302–308, 2018, doi: 10.1109/URAI.2018.8441920.

[24] D. Sosa-Mendez, "Development of an exoskeleton for shoulder rehabilitation," *Mixteca Technological University*, Oax, MEX. 2017, doi: 10.1109/CSPA.2015.7225642.

[25] C. A. Anirudh Sharma, A. S. Karthik Sai Vishnu Kumar, A. Prasad, R. Begum, G. S. Sharvani, and A. E. Manjunath, "Multifaceted bio-medical applications of exoskeleton: A

review," Proc. 2nd Int. Conf. Inv. Sys. Control, pp. 11-15, 2018, doi: 10.1109/ICISC.2018.8399053.

[26] N. Yagn, "Apparatus for facilitating walking, running, and jumping," Pat. 420.179, US420179A, Jan 28, 1890.

[27] L. C. Kelley, "Pedomotor," US1308675 A, 1919.

[28] Y. Horiuchi, T. Kishi, J. Gonzalez, and W. Yu, "A study on classification of upper limb motions from around-shoulder muscle activities," IEEE Int. Conf. Rehabil. Robot., 311-315, 2009, doi: 10.1109/ICORR.2009.5209477.

[29] B. Ugurlu, M. Nishimura, K. Hyodo, M. Kawanishi, and T. Narikiyo, "Proof of Concept for Robot-Aided Upper Limb Rehabilitation Using Disturbance Observers," *IEEE Trans. Human-Machine Syst*., vol. 45, no. 1, pp. 110-118, Nov 2014, doi:10.1109/THMS.2014.2362816

[30] M. H. Rahman, M. Saad, J. P. Kenné, and P. S. Archambault, "Exoskeleton Robot for Rehabilitation of Elbow and Forearm Movements," 18th Mediterr. Conf. Control Autom., pp. 1567-1572, 2010, doi: 10.1109/MED.2010.5547826.

[31] V. Crocher, N. Jarrassé, A. Sahbani, A. Roby-Brami, and G. Morel, "Changing human upper-limb synergies with an exoskeleton using viscous fields," *IEEE Int. Conf. Robot. Autom.,* pp, 4657-4663, 2011, doi: 10.1109/ICRA.2011.5979626.

[32] A. L. Delis, L. M. Revilla, D. D. Rodriguez, and A. F. R. Olaya, "On the use of surface EMG for recognizing forearm movements: Towards the control of an upper extremity exoskeleton," *6th Andean Reg. Int. Conf*., pp. 181-184, 2012, doi: 10.1109/CIBEC.2012.6424146.

[33] Y. Morita, T. Yamamoto, R. Tanioku, M. Uchida, H. Ukai, and N. Matsui, "Analysis and modeling of upper limb motion during sanding training," *Int. Conf. Control. Autom. Syst.*, pp. 1585-1590, 2007, doi: 10.1109/ICCASE.2007.4406613.

[34] K. Kiguchi, T. Tanaka, and T. Fukuda, "Neuro-fuzzy control of a robotic exoskeleton with EMG signals," *IEEE Trans. Fuzzy Syst*., vol. 12, no. 4, pp. 481-490, 2004, doi:10.1109/TFUZZ.2004.832525

[35] Z. G. Xiao, A. M. Elnady, and C. Menon, "Control an exoskeleton for forearm rotation using FMG," *5th IEEE RAS/EMBS Int. Conf. Biomed. Robot Biomechatronics*, pp. 591-596, 2014, doi: 10.1109/BIOROB.2014.6913842.

[36] A. U. Pehlivan, S. Lee, and M. K. O'Malley, "Mechanical Design of RiceWrist-S: a Forearm-Wrist Exoskeleton for Stroke and Spinal Cord Injury Rehabilitation," *4th IEEE RAS & EMBS,* pp. 1573-1578, 2012, doi: 10.1109/BioRob.2012.6290912.

[37] M. R. Islam, C. Spiewak, M. H. Rahman, and R. Fareh, "A Brief Review on Robotic Exoskeletons for Upper Extremity Rehabilitation to Find the Gap between Research Porotype and Commercial Type," *Adv. Robot. Autom.*, vol.6, no.3, 2017, doi:10.4172/2168-9695.1000177.

[38] F. Blaya, P. S. Pedro, J. L. Silva, R. D'Amato, E. S. Heras, and J. A. Juanes, "Design of an Orthopedic Product by Using Additive Manufacturing Technology: The Arm Splint," *J. Med. Syst*., vol. 42, no. 3, 2018, doi:10.1007/s10916-018-0909-6.

[39] J. Garrido, W. Yu, and A. Soria, "Modular Design and Modeling of an Upper Limb Exoskeleton," *5th IEEE RAS/EMBS Int. Conf. Biomed. Robot. Biomechatronics*, pp. 508-513, Sao Paulo, BRA, Oct 2014, doi: 10.1109/BIOROB.2014.6913828.

[40] N. Klopčar and J. Lenarčič, "Kinematic model for determination of human arm reachable workspace," *Meccanica,* vol. 40, no. 2, pp. 203-219, 2005, doi:10.1007/s11012-005-3067-0.

[41] J. C. Perry, J. Rosen, and S. Burns, "Upper-limb powered exoskeleton design," IEEE/ASME Trans. Mechatron., vol. 12, no. 4, pp. 408-417, 2017, doi:10.1109/TMECH.2007.901934.

[42] K. L. Moore, A. F. Dailey, and A. M. R. Agur, "Anatomy with clinical orientation" vol. 53, no. 9, 2023, ISBN: 978-1975209544.

[43] J. M. P. Gunasekara, R. a. R. C. Gopura, T. S. S. Jayawardane, and S. W. H. M. T. D. Lalitharathne, "Control methodologies for upper limb exoskeleton robots," *IEEE/SICE Int. Symp. Syst. Integr*., pp. 19-24, Fokouka, JPN, Dec 2012, doi: 10.1109/SII.2012.6427387.

[44] R. A. R. C. Gopura, D. S. V. Bandara, K. Kiguchi, and G. K. I. Mann, "Developments in hardware systems of active upper-limb exoskeleton robots: A review," *Rob. Auton. Syst.,* vol. 75, pp. 203-220, 2016, doi: 10.1016/j.robot.2015.10.001.

[45] R. Arachchilage, R. Chandra, and K. Kiguchi, "EMG-Based Control of an Exoskeleton Robot for Human Forearm and Wrist Motion Assist," *IEEE Int. Conf. Robot. Autom.,* 731-736, Pasadena, USA, May 2008 doi: 10.1109/ROBOT.2008.4543292.

[46] J. Lee, M. Kim, S. Oh, and K. Kim, "Integrated Control Method for Power-Assisted Rehabilitation: Ellipsoid Regression and Impedance Control," *Int. Conf. Intell. Robot. Sys.*, pp. 2101-2106, Chicago, USA, Sep 2014 doi: 10.1109/IROS.2014.6942844.

[47] C.-W. Chu, O. C. Jenkins, and M. J. Matarié, "Markerless kinematic model and motion capture from volume sequences," *IEEE Comput. Soc. Conf. Comput. Vis. Pattern Recognition*., vol. 2, pp. 475-482, Madison, USA, Jul 2003, doi: 10.1109/CVPR.2003.1211505.

[48] J. C. Perry, J. M. Powell, and J. Rosen, "Isotropy of an upper limb exoskeleton and the kinematics and dynamics of the human arm," *Appl. Bionics Biomech.*, vol. 6, no. 2, pp. 175-191, 2009, doi: 10.1080/11762320902920575.

[49] A. U. Pehlivan, C. Rose, and M. K. O'Malley, "System Characterization of RiceWrist-S : a Forearm-Wrist Exoskeleton For Upper Extremity Rehabilitation," IEEE Int. Conf. Rehabil. Robot., 2, 1-6, doi:10.1109/ICORR.2013.6650462 (2013).

[50] Rehabilitation," *IEEE Int. Conf. Rehabil. Robot*., vol. 2, pp. 1-6, Seattle, USA, Oct 2013.

[51] Y. Li, Z. Guo, and K. Wang, "A BP Neural Network Based Method for Upper Limb Motion Intensity Evaluation," *Int. Conf. Cloud Comput. Big Data*, pp. 171-176, Fuzhou, CHN, May 2014, doi: 10.1109/ROBIO.2009.5420466.

[52] M. A. Destarac, C. E. García, J. García, R. Espinoza, and R. J. Saltarén, "ORTE : Robot for Upper Limb Rehabilitation . Biomechanical Analysis of Human Movements," *IEEE Lat. Am. Trans.,* vol.16 no. 6, pp. 1638-1643, 2018, doi:10.1109/TLA.2018.8444160

[53] A. S. Niyetkaliyev, S. Hussain, M. H. Ghayesh, and G. Alici, "Review on Design and Control Aspects of Robotic Shoulder Rehabilitation Orthoses," *IEEE Trans. Human-Machine Syst*., vol. 47, no.6, pp. 1134–1145, 2017, doi:10.1109/THMS.2017.2700634.

[54] J. Rosen, M. Brand, M. Fuchs, and M. Arcan, "A myosignal-based powered exoskeleton system," *IEEE Trans. Syst. Man, Cybern. - Part A Syst. Humans*, vol. 31, no. 3, pp. 210-222, 2001, doi: 10.1109/3468.925661.

[55] H. Guo et al., "Prediction of twist angle for assistive exoskeleton based on EMG signals," *IEEE 3rd Int. Conf. Data Sci. Cyberspace*, pp. 819-823, Guangzhou, CHN, Jul 2018, doi: 10.1109/DSC.2018.00131.

[56] P. Marian, I. Danuţ, P. Nirvana, and P. Dorin, "Engineered devices to support stroke rehabilitation," *19th Int. Conf. Control Syst. Comput. Sci*., pp. 289-95, Bucharest, ROU, Jul 2013, doi: 10.1109/CSCS.2013.44.

[57] S. Bembli, N. K. Haddad, and S. Belghith, "Robustness analysis of an upper-limb exoskeleton using Monte Carlo simulation," *Int. Conf. Adv. Syst. Electr. Technol.*, pp. 78-84, Hammamet, TT, Jun 2018, doi: 10.1109/ASET.2018.8379838.

[58] B. Brahmi, M. Saad, C. Ochoa Luna, M. H. Rahman, and A. Brahmi, “Adaptive Tracking Control of an Exoskeleton robot with Uncertain Dynamics Based on Estimated Time Delay Control,” *IEEE/ASME Trans. Mechatronics*, vol. 23, no. 2, pp. 575-585, 2018, doi: 10.1109/TMECH.2018.2808235.

[59] E. Sánchez, A. Luviano, and A. Rosales, “A robust GPI controller for trajectory tracking tasks in the limbs of a walking robot*,” Int. J. Control. Autom. Syst.*, vol. 15, no. 6, pp. 2786-2795, 2017, doi:10.1007/s12555-015-0387-2.

[60] T. Proietti, V. Crocher, A. Roby-Brami, and N. Jarrasse, “Upper-limb robotic exoskeletons for neurorehabilitation: A review on control strategies,” *IEEE Rev. Biomed. Eng*., vol. 9, pp. 4-14, 2016, doi: 10.1109/RBME.2016.2552201.

[61] A. Gupta, M. K. O’Malley, V. Patoglu, and C. Burgar, “Design, Control and Performance of RiceWrist: A Force Feedback Wrist Exoskeleton for Rehabilitation and Training,” *Int. J. Rob. Res*., vol. 27, pp. 233-251, 2008, doi:10.1177/0278364907084261.

[62] Y. Jung and J. Bae, “Kinematic analysis of a 5-DoF upper-limb exoskeleton with a tilted and vertically translating shoulder joint,” *IEEE/ASME Trans. Mechatronics*, vol. 20, no. 3, pp. 1428-1439, 2015, doi:10.1109/TMECH.2014.2346767.

[63] A. Kinematc and D. Requirements, “Design and development of a human-machine interactive-force controlled powered upper-limb exoskeleton for human augmentation and physical rehabilitation,” *Int. Conf. Biomed. Eng. Scien.*, pp. 465-470, Langkawi, Dec 2012, doi: 10.1109/ICM.2017.8013349.

[64] M. B. Hong, S. J. Kim, and K. Kim, “Development of a 10-DoF robotic system for upper-limb power assistance,” *9th Int. Conf. Ubiquitous Robots. Amb. Intell.*, pp. 61-62, Daejeon, KOR 2012, doi: 10.1109/URAI.2012.6462931.

[65] M. H. Rahman, M. Saad, J. P. Kenné, and P. S. Archambault, “Control of a powered exoskeleton for elbow, forearm and wrist joint movements,” *IEEE 11th Int. Conf. Robot. Biomimetics*, pp. 1561-1566, Karon, TH, April 2012, doi: 10.1109/ROBIO.2011.6181511.

[66] S. Zhang, S. Guo, M. Qu, and M. Pang, “Development of a Bilateral Rehabilitation Training System Using the Haptic Device and Inertia Sensors,” *IEEE Int. Conf. Mechatronics Autom.,* pp. 606–611, Tianjin, CHN, August 2014, doi: 10.1109/ICMA.2014.6885766.

[67] W. Wei, S. Guo, W. Zhang, J. Guo, and Y. Wang, “A novel VR-based upper limb rehabilitation robot system,” *ICME Int. Conf. Complex Med. Eng. C.*, vol. 5, pp.302-306, Beijing, CHN, Jun 2013, doi: 10.1109/ICCME.2013.6548259.

[68] Z. Song, S. Guo, M. Pang, and S. Zhang, “ULERD-based active training for upper limb rehabilitation,” *IEEE Int. Conf. Mechatronics Autom*., pp. 569-574, Chengdu, CHN, Aug 2012, doi: 10.1109/ICMA.2015.7237937.

[69] H. Kimura, E. Genda, K. Nakamura, H. Tanaka, and H. Kawasaki, “Development of Upper-Limb Motion-Assist Device for High Cervical Spinal Cord Injury,” SICE Annu. Conf., pp. 1–6, Sapporo, JPN, Oct, 2014, doi: 10.1109/ROBIO.2012.6491040.

[70] H.-B. Kang, J.-H. Wang, L.-Y. Yu, L. Xu, and Ieee, “Adaptive controller design for upper-limb rehabilitation robot,” *25th Chinese Control Decis. Conf.*, pp. 2626–2631, Guiyang, CHN, Jul, 2013, doi: 10.1109/CCDC.2013.6561384.

[71] Y. J. Kim, C. K. Park, and K. G. Kim, “An EMG-based variable impedance control for elbow exercise: preliminary study,” *Adv. Robot.,* vol. 31, no. 15, pp. 809-820, 2017, doi:10.1080/01691864.2017.1353440

[72] Y. J. Kim, C. K. Park, and K. G. Kim, “An EMG-based variable impedance control for elbow exercise: preliminary study,” *Adv. Robot*., vol. 31, no. 15, pp. 809-820, 2017, doi:10.1080/01691864.2017.1353440

[73] A. Abooee, M. M. Arefi, F. Sedghi, and V. Abootalebi, “Robust nonlinear control schemes for finite-time tracking objective of a 5-DoF robotic exoskeleton,” *Int. J. Control*, vol. 7179, pp. 1-16, 2018, doi:10.1080/00207179.2018.1430379.

[74] V. Crocher, J. Fong, T. Bosch, Y. Tan, I. Mareels, and D. Oetomo, “Upper Limb Deweighting using Underactuated End-effector based Backdrivable Manipulanda,” *IEEE Robot. Autom. Lett*., vol. 3, no. 3, pp. 2116-2122, 2018, doi:10.1109/LRA.2018.2809605.

[75] J. Zheng, P. Shi, and H. Yu, “A Virtual Reality Rehabilitation Training System Based on Upper Limb Exoskeleton Robot,” *10th Int. Conf. Intell. Human-Machine Syst. Cybern*., pp. 220-223, Hangzhou, CHN, Nov 2018, doi: 10.1109/IHMSC.2018.00058.

[76] S. Pei, J. Wang, J. Guo, et al, “A Human-like Inverse Kinematics Algorithm of an Upper Limb Rehabilitation Exoskeleton”, *Symmetry*, vol. 15, no. 1657, pp. 1-17, 2023, doi: 10.3390/sym15091657

[77] I. Abdallah, Y. Boutera., “An Optimized Stimulation Control System for Upper Limb Exoskeleton Robot-Assisted Rehabilitation Using a Fuzzy Logic-Based Pain Detection Approach”, *Sensors*, vol. 24, pp. 2-17, 2024, doi: 10.3390/s24041047.

[78] H. Li, S. Guo, H. Wang. D. Bu, “Preliminary Exploration of Haptic-enabled Therapist-in-the-Loop Telerehabilitation System for Exoskeleton-assisted Upper Limb Training,” *Int. Conf. Mechatronics Autom*., vol.9, pp 1984-1989, Heilongjiang, CHN, Aug 2023, doi: 10.1109/ICMA57826.2023.10216246.

[79] P. Ni, J. Sun, J Dong, “Design and Control of an Upper Limb Bionic Exoskeleton Rehabilitation Device Based on Tensegrity Structure”, *Wiley,* vol.2024, pp. 1-15,2024, doi*:*10.1155/2024/5905225.

[80] Q. Meng, Q. Xie, H. Shao, “Pilot study of a Powered Exoskeleton for Upper Limb Rehabilitation Based on the Wheelchair”, *Hindawi*, Vol. 2019, pp 1-11, doi: 10.1155/2019/9627438.

[81] M. Burns, Z. Zavoda, R. Nataraj, et. al, “HERCULES: A Three Degree-of-Freedom Pneumatic Upper Limb Exoskeleton for Stroke Rehabilitation,” *Ann. Inter. Conf. Eng. Medicine and Biology Soc.* pp. 4459-4462 doi:10.1109/EMBC44109.2020.9176549, Jul. 2022.

[82] P. Rangan, J. Johnson, R. Babu, et al, “Desing and Modelling of a Human Upper Limb for Rehabilitation Exoskeleton,” *JESTR*, vol. 17, num. 2, pp. 9-15, 2024, doi:10.25103/jestr.172.02.

[83] S. Hu, X. Zhou, J. Bao, “Graded Optimization of Upper Limb Exoskeleton Parts for Grid Operations,” *IEEEAccess*, vol. 11, pp. 14409-14417, 2023, doi: 10.1109/ACCESS.2023.3243942.

[84] J. Gou, P. Li, and S. Gou, “Design and Analysis of a Wearable Exoskeleton Upper Limb Rehabilitation Robot,” *Int. Conf. Mechatronics Autom.*, pp. 1564-1569, doi: 10.1109/ICMA49215.2020.9233873, Beijing, CHN, 2020

[85] J. Nuñez, D. Campusano, et. al., "Performance comparison between PD and PID Controller in an upper limb Exoskeleton by analyzing an arm trajectory modeled with Image Recognition," *Eng. Int. Res. Conf. (EIRCON)*, pp. 1-4, doi: 10.1109/EIRCON51178.2020.9254082. Lima, PE, 2020.

[86] D. Chiaradia, G. Rinaldi, M. Solazzi, et.al., “Design and Control of the Rehab-Exos, a Joint Torque-Controlled Upper Limb Exoskeleton,” *Robotics,* vol. 13, num. 32, pp. 1-29 doi: 10.3390/robotics13020032, 2024.

[87] D. Ito, M. Fukuda, Y. Hosoi, et.al., “Optimizing shoulder elevation assist rate in exoskeletal rehabilitation based on muscular activity indices: a clinical feasibility study,” *BMC Neurology,* vol. 24, num. 144, pp.1-10, doi:10.1186/s12883-024-03651-x, 2024.

[88] T. Ahmed, R. Islam, B Brahmi, M Rahman, "Robustness and Tracking Performance Evaluation of PID Motion Control of 7 DoF Anthropomorphic Exoskeleton Robot Assisted Upper Limb Rehabilitation," *Sensors*, vol. 22, num. 3747, pp. 1-26, doi: 10.3390/s22103747, 2022.

[89] S. Pei, J. Wang, J. Guo, H. Yin, Y. Yao, "A Human-like Inverse Kinematics Algorithm of an Upper Limb Rehabilitation Exoskeleton," *Symmetry*, vol. 15, num. 1657, pp 1-17, doi: 10.3390/sym15091657, 2023.

[90] T.M. Kwok, T. Li. And H. Yu, "A Reliable Kinematic Measurement of Upper Limb Exoskeleton for VR Therapy with Visual-inertial Sensors*". Int. Conf. on Adv. Intel. Mechatronic*, pp 584-590, Seattle, USA, Jun 2023. Doi: 10.1109/AIM46323.2023.10196192

[91] H. Morishita, T Murakami, "Assistance Torque Control Based on Musculoskeletal Hexagon Output Distribution for Upper Limb Exoskeleton", *Int. Conf. on Mechatronics*, pp 1-6, Loughborough, UK, March 2023, doi: 10.1109/ICM54990.2023.10101922

[92] M.H. Yen, L. H. Yao et al. "Development of an Upper Limb Exoskeleton System with Integrated Electromyography Signals", *Int. Sym. On Computer, consumer and Control*, pp. 244-248, Taichung, TW, Jun/Jul 2023, doi: 10.1109/IS3C57901.2023.00072

[93] M. Abdallah, R. Fareh, Y. Kali, and M. Bettayeb, "Reinforcement Learning Human Inverse Kinematics of a Upper Limb Exoskeleton Robot", *Adv in Scs. Tech. Int. Conf.* pp. 1-6, Dubai, UAE, doi: 10.1109/ROBIO.2018.8665249.

[94] C. Liu, J. Wen, P Zhu, "Upper limb and Back Rehabilitation Exoskeleton", *Inter. Conf. On Electrical, Automation and Eng.*, pp 206-212, Changchun, CH, Dec. 2023. doi: 10.1109/ICEACE60673.2023.10442916

[95] R. F. Chandler, C. E. Clauser, J. T. McConville, H. M. Reynolds, and J. W. Young, "Investigation of inertial properties of the human body," Natl. Highw. *Traffic Saf. Adm*., vol. 3, pp. 1-169, 1975, doi:10.1017/CBO9781107415324.004.

[96] S. H. Elwardany, W. H. El-Sayed, and M. F. Ali, "Reliability of Kinovea Computer Program in Measuring Cervical Range of Motion in Sagittal Plane," *Open Access Libr. J*., vol. 2. No. 9, pp. 1-10, 2015, doi:10.4236/oalib.1101916.

[97] J. L. Guzmán-Valdivia, C.H., Blanco-Ortega, A., Oliver-Salazar, M.A.y Carrera-Escobedo, "Therapeutic Motion Analysis of Lower Limbs Using Kinovea," Int. J. Soft Comput. Eng., vol. 3, no. 2, pp. 359-365, 2013, doi:10.1016/S0032-9592(96)00006-4.

[98] W. Wei, S. Guo, W. Zhang, J. Guo, and Y. Wang, "A novel VR-based upper limb rehabilitation robot system," *ICME Int. Conf. Complex Med. Eng. C*., vol. 5, pp.302-306, Beijing, CHN, Jun 2013, doi: 10.1109/ICCME.2013.6548259.

[99] H.-B. Kang, J.-H. Wang, L.-Y. Yu, L. Xu, and Ieee, "Adaptive controller design for upper-limb rehabilitation robot," *25th Chinese Control Decis. Conf*., pp. 2626-2631, 2013, doi:. 10.1163/016918610X538561

[100] H. A. Al-Hajjar, S. A. Ahmad, M. H. Marhaban, A. J. Isha, "An Optimized Stimulation Control System for Upper Limb Exoskeleton Robot-Assisted Rehabilitation Using a Fuzzy Logic-Based Pain Detection Approach," *IEEE Access,* vol. 10, pp. 106093-106108, 2022, doi: 10.1109/ACCESS.2022.3211516

[101] https://www.hocoma.com/de/losungen/armeo-spring-pro/

Luis Vázquez-Sánchez is currently pursuing a postdoctoral degree at the Universidad Tecnológica de la Mixteca in the state of Oaxaca, Mexico. He obtained the title of Electronics Engineer at the TecNM-Instituto Tecnológico de Cuautla; He obtained the degree of Master of Science in Electronic Engineering at the TecNM-National Center for Technological Research and Development (CENIDET) and the degree of Doctor of Science in Mechanical Engineering at the same CENIDET. He is currently working on robust control, exoskeletons for rehabilitation and mobile vehicles.

Manuel Arias-Montiel received the B.S. degree in mechanical engineering from the Universidad Autónoma Metro-politana, México, and the M.Sc. and Ph.D degrees in electrical engineering (mechatronics) from CINVESTAV (IPN), México. He is currently a titular researcher in the Institute of Electronics and Mechatronics of the Universidad Tecnológica de la Mixteca in Oaxaca, México. He is an IEEE and ASME member, and he is the author of articles published in international journals and conferences. His research interests are in analysis and control of mechanical vibrations, mobile robots, and rehabilitation robotics.

Manuel Adam-Medina received the Professional Diploma degree in electronic engineering of instrumentation from the Minatitlán Institute of Technology, Minatitlán, in 1991, the M.Sc. degree in electronics engineering from National Center for Research and Technological Development (CENIDET), Cuernavaca, Mexico, in 1995, and the Ph.D. degree in engineering from Henri Poincaré University, Nancy, France, in 2004. He is currently a Professor with the Department of Electronic Engineering, CENIDET. His research interests include fault-tolerant control and fault diagnosis systems.

Carlos Daniel Garcia-Beltran is a researcher at the National Center for Research and Technological Development (CENIDET), specializing in modeling, simulation, and control of dynamic systems. He earned a Ph.D. in Automatic Control and Production Engineering from the Institut National Polytechnique de Grenoble. He is a Level I member of the National System of Researchers (SNI). His work focuses on fault-tolerant control, aerial robotics, and power electronics, with numerous publications in indexed journals and participation in national and international research projects.